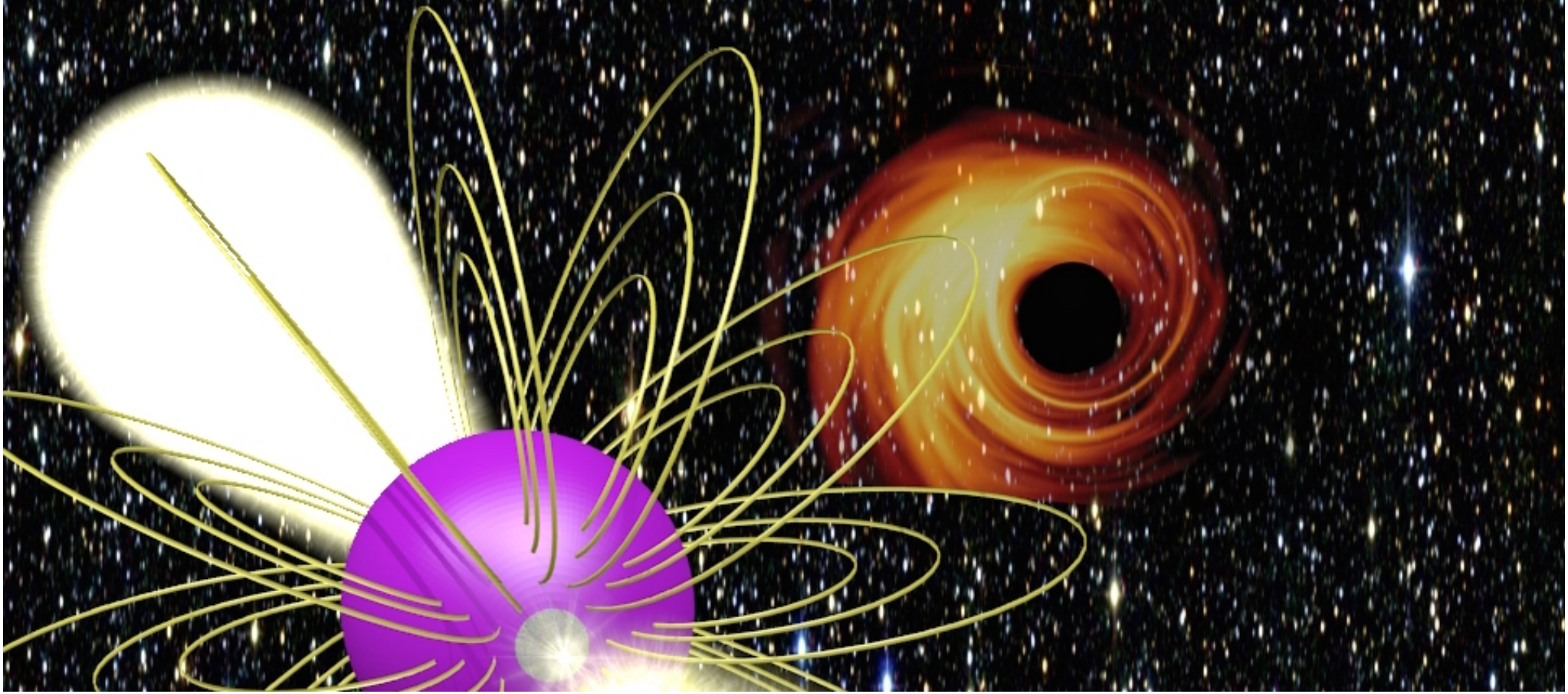
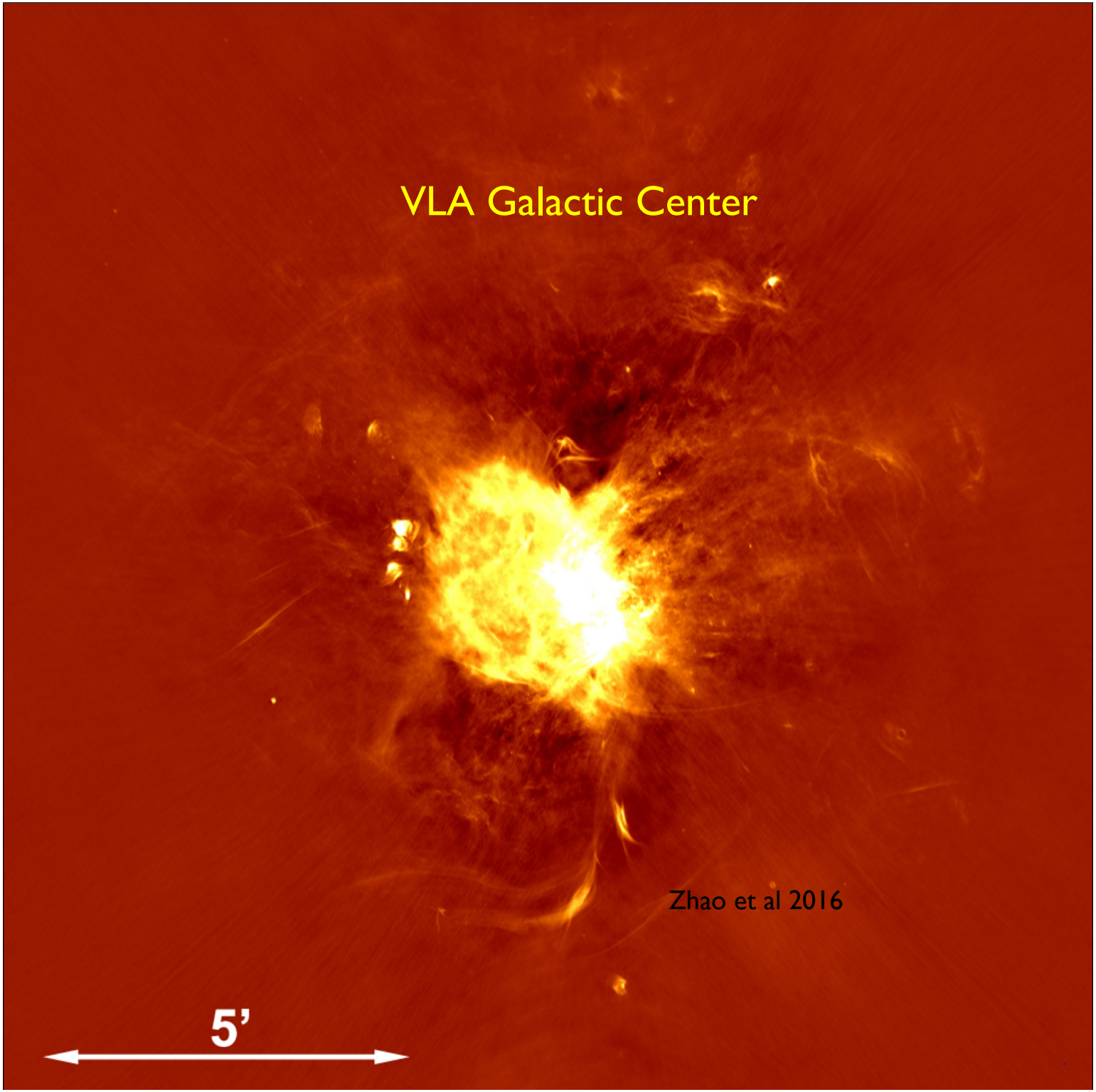
Approaching the Event Horizon with Sagittarius A*

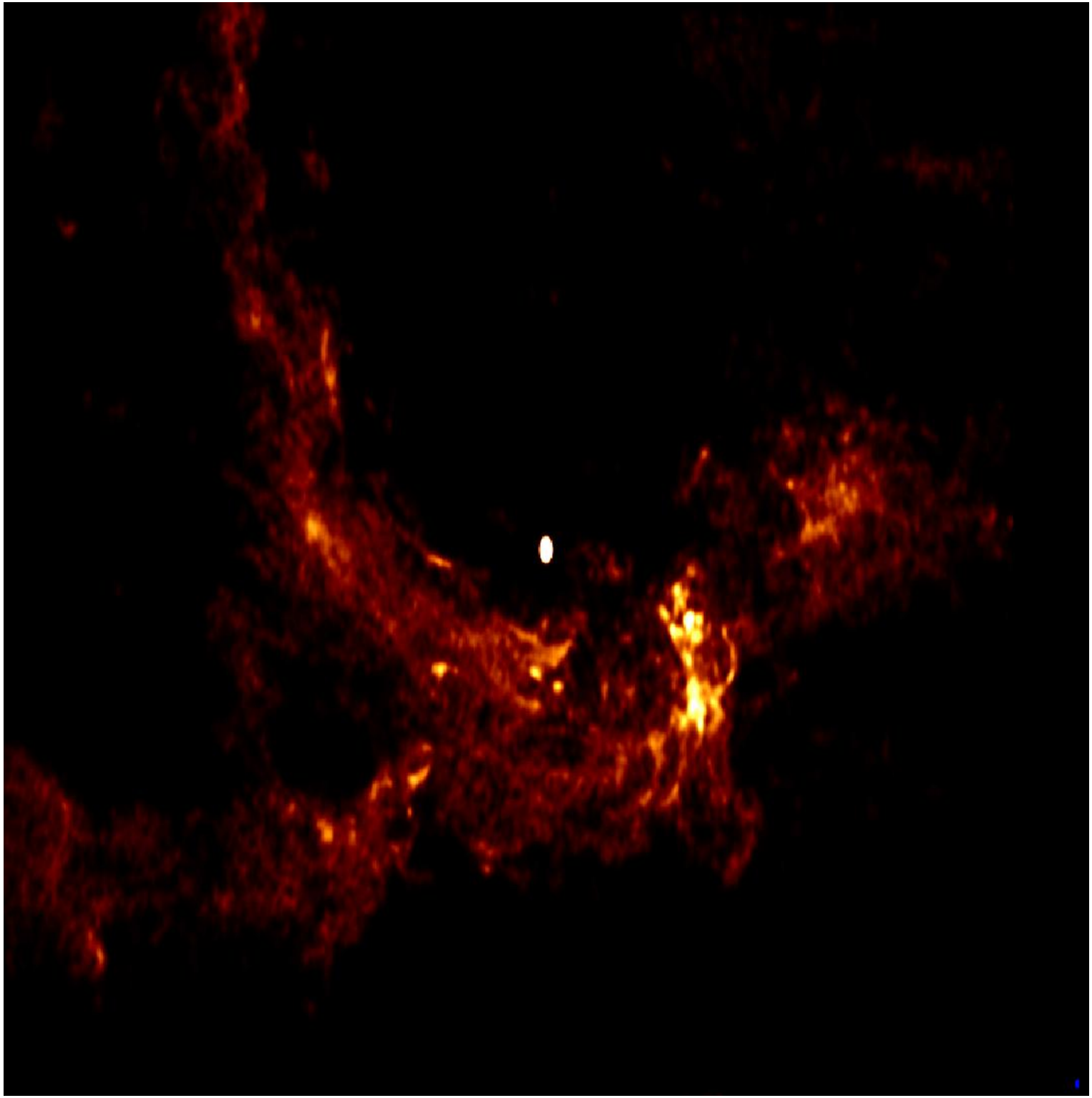
Geoffrey C. Bower

(ASIAA, Hilo)

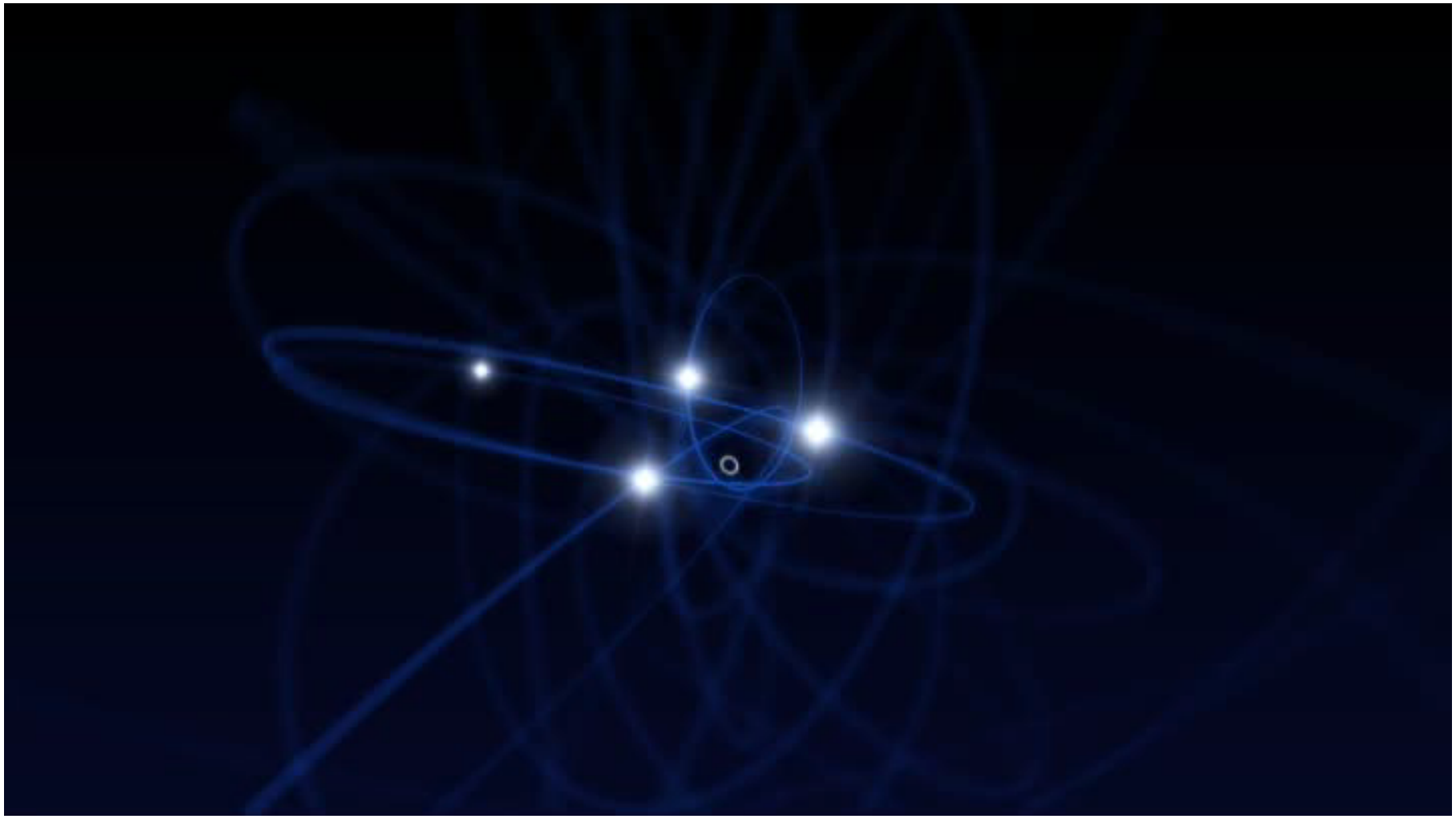



Mauna Loa, Hawaii
1984


VLA Galactic Center
Zhao et al 2016
5’

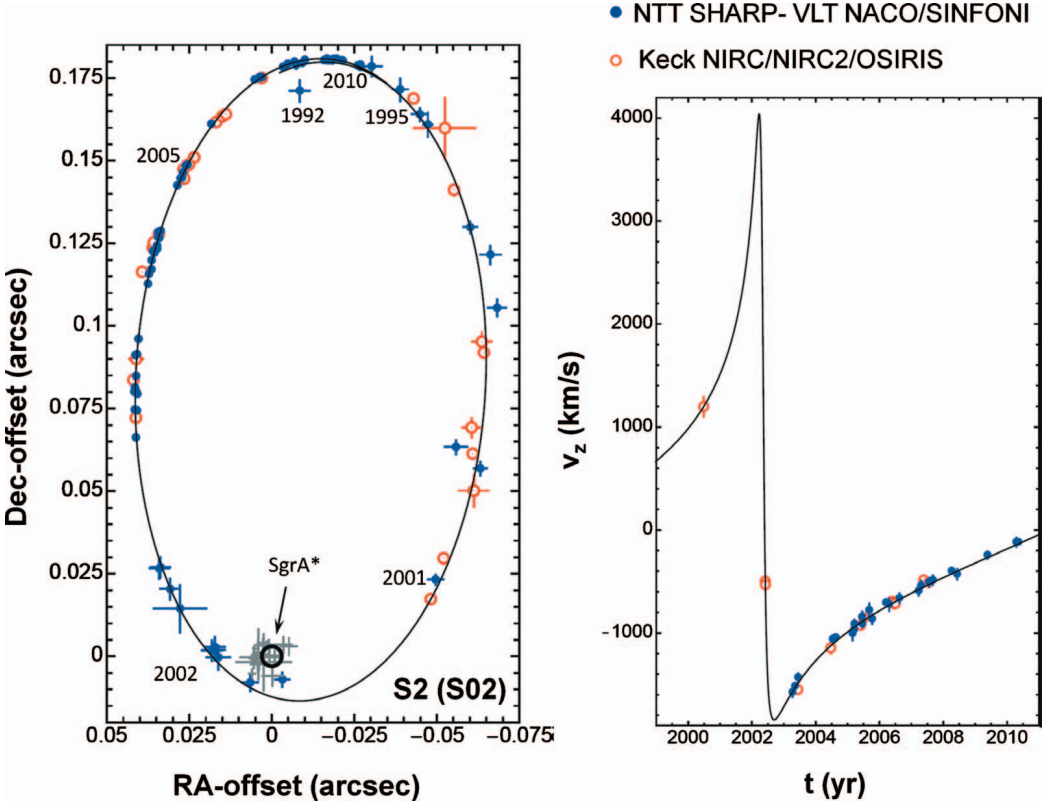


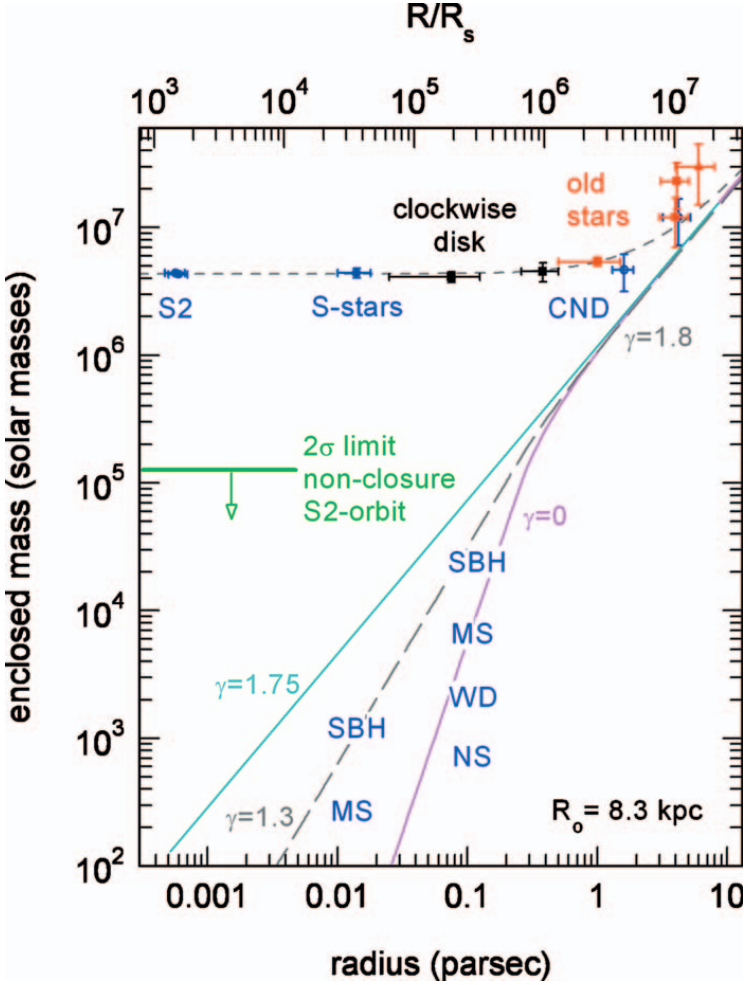
Stellar Orbits Around Sgr A*



Genzel, Gillessen et al

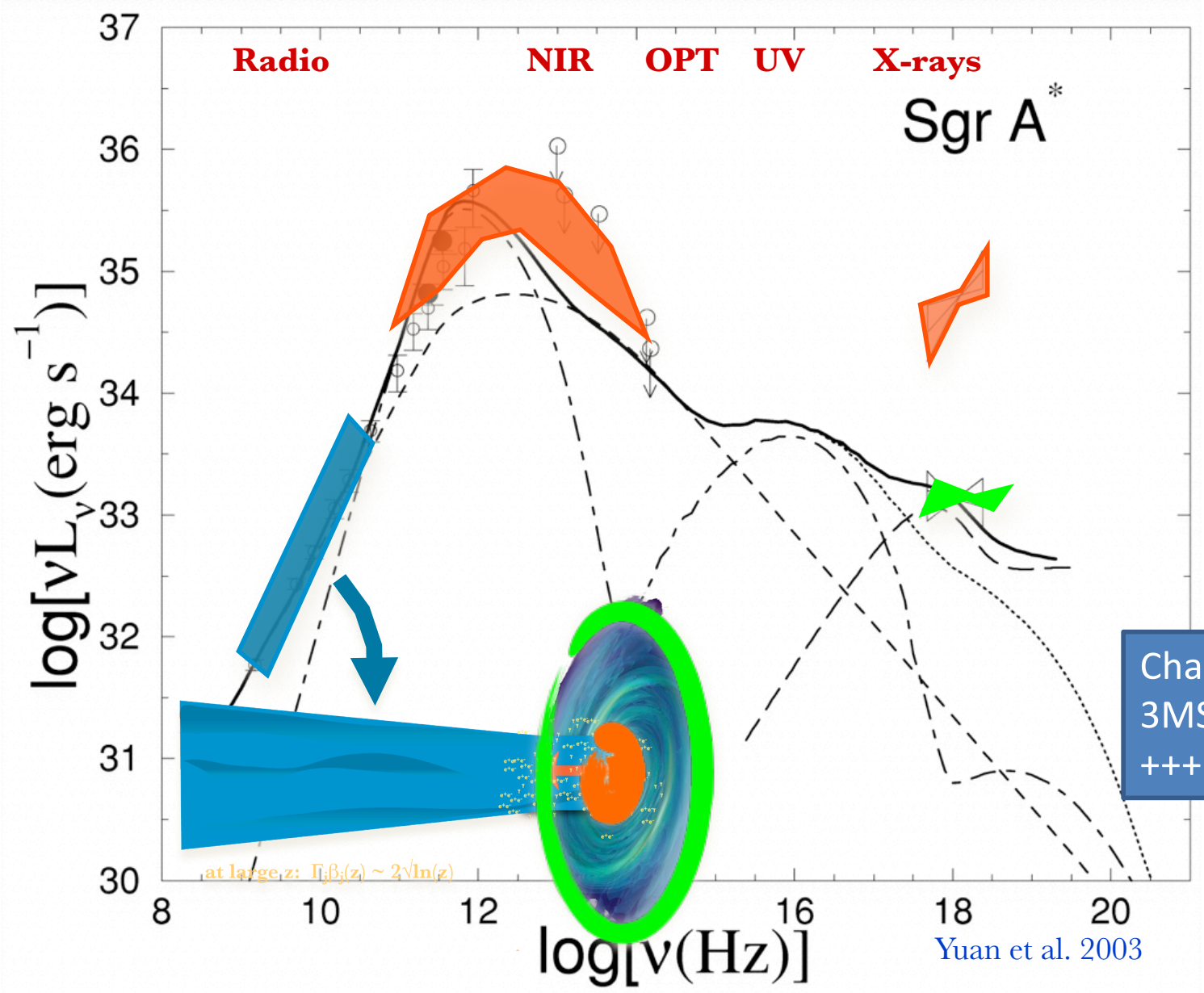
Strong Evidence for a Black Hole



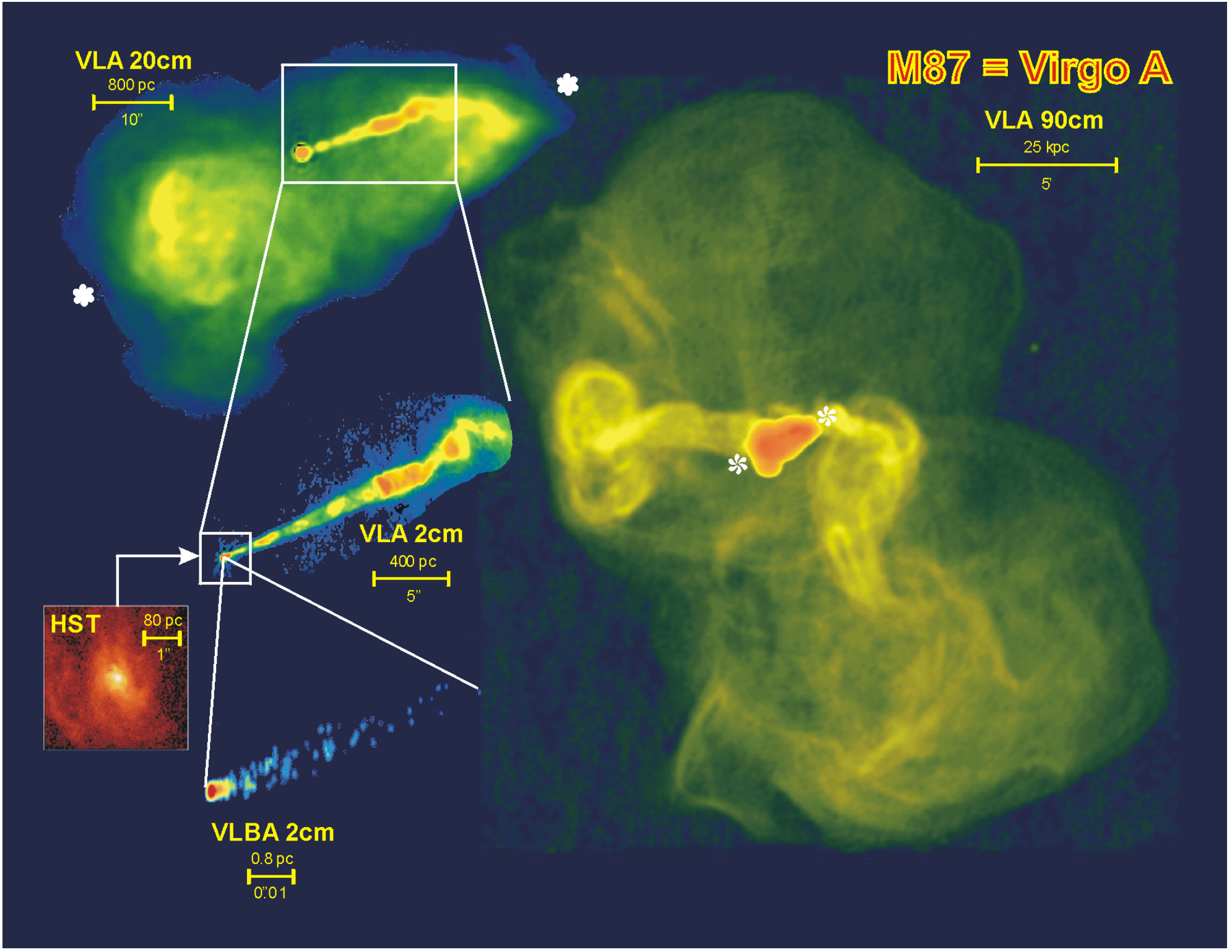


Genzel et al 2010

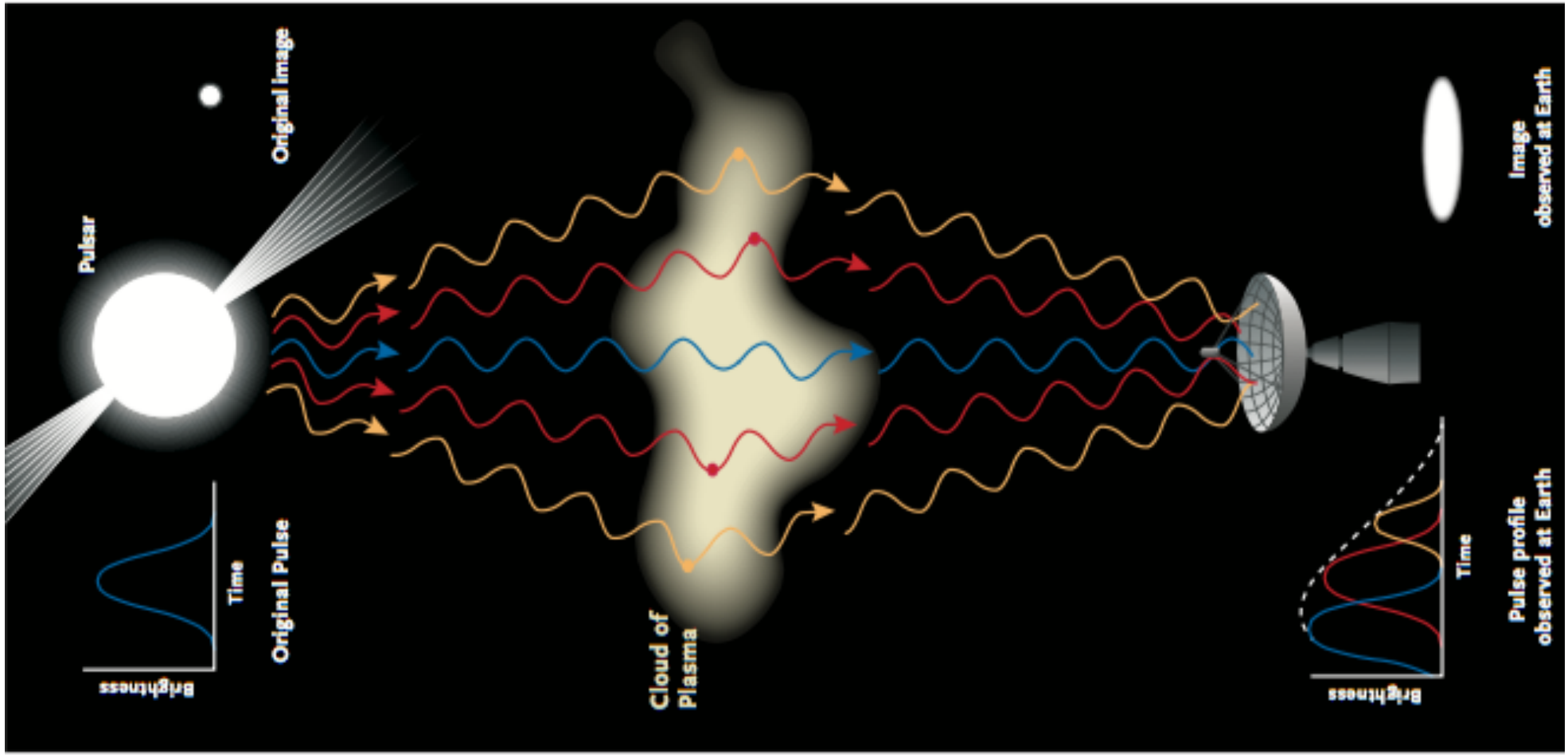
Rich Phenomenology --- Jets and Disks



Chandra XVP
3MS campaign
+++

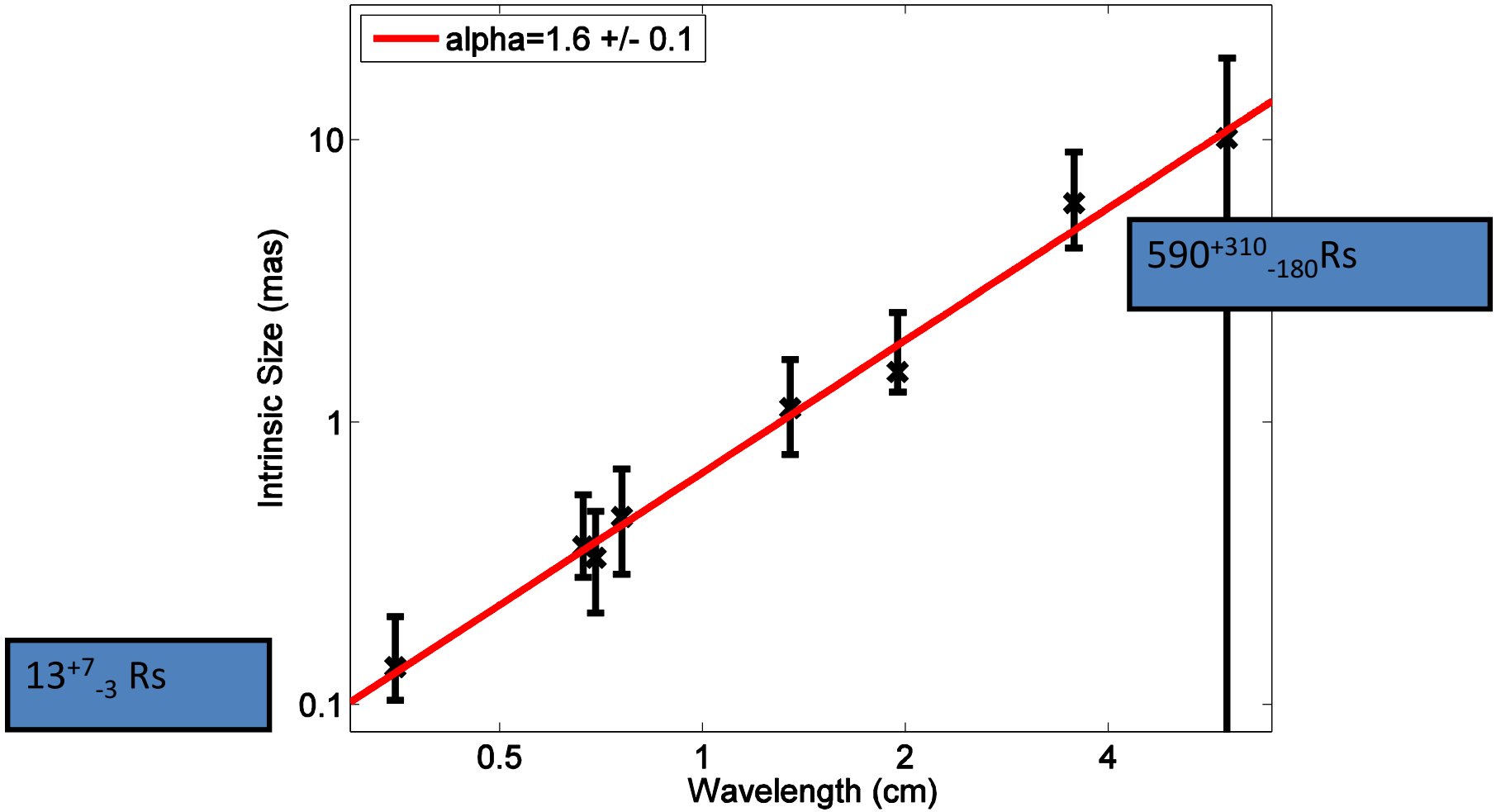

M87 = Virgo A
VLA 90cm
25 kpc
5'
VLA 20cm
800 pc
10"
VLA 2cm
400 pc
5"
HST
80 pc
1"
VLBA 2cm
0.8 pc
0".01

Scattering Inhibits Imaging



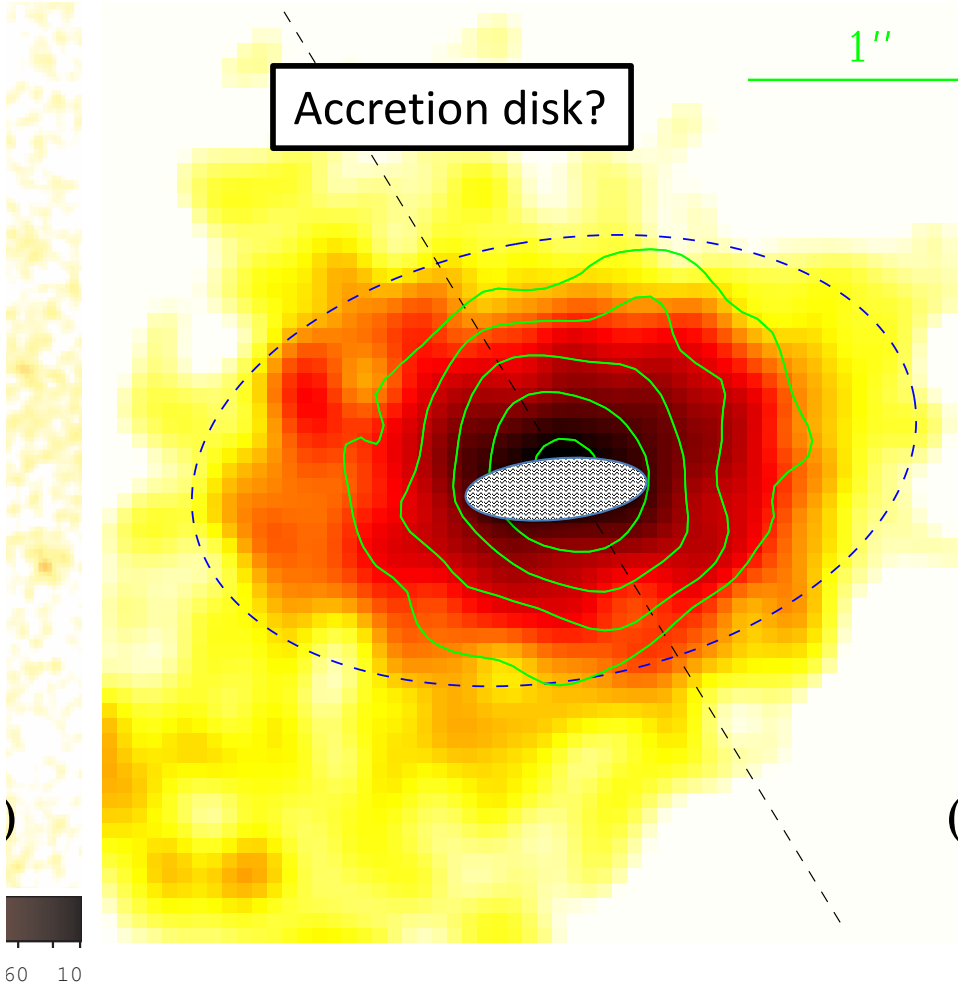
Haggard & Bower, Sky & Tel, 2016

The Intrinsic Size of Sgr A*

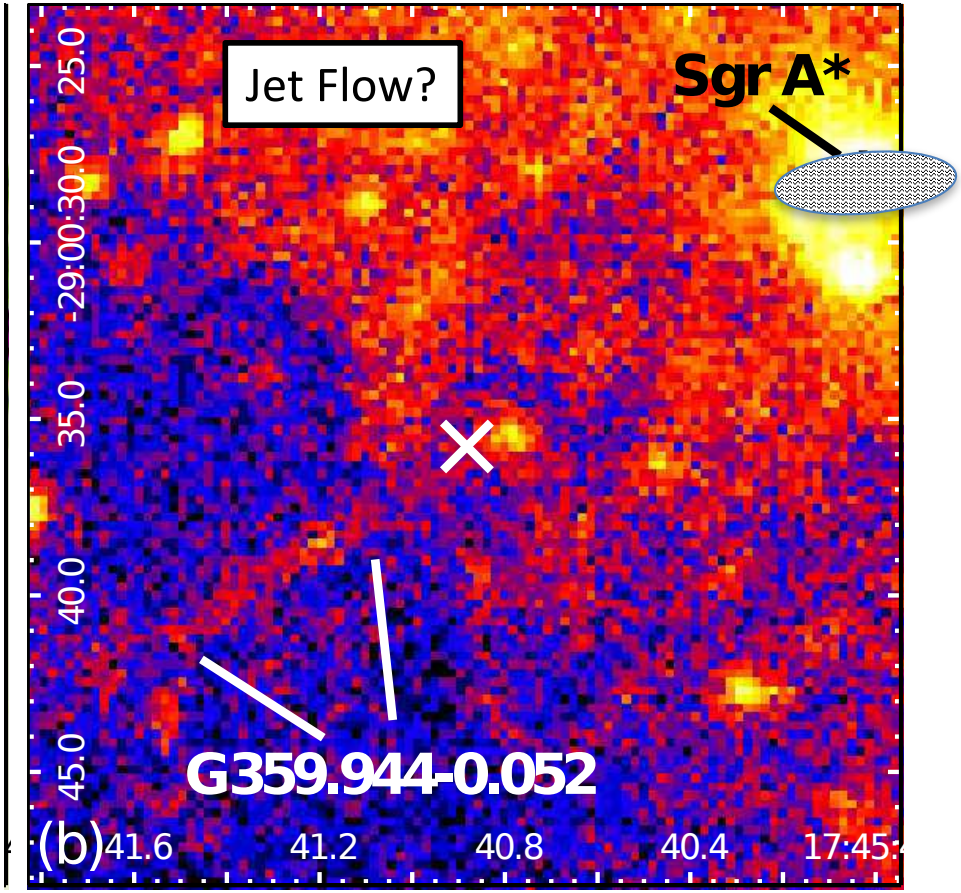


Bower et al 2006

Jet Orientation from 7mm VLBA Imaging



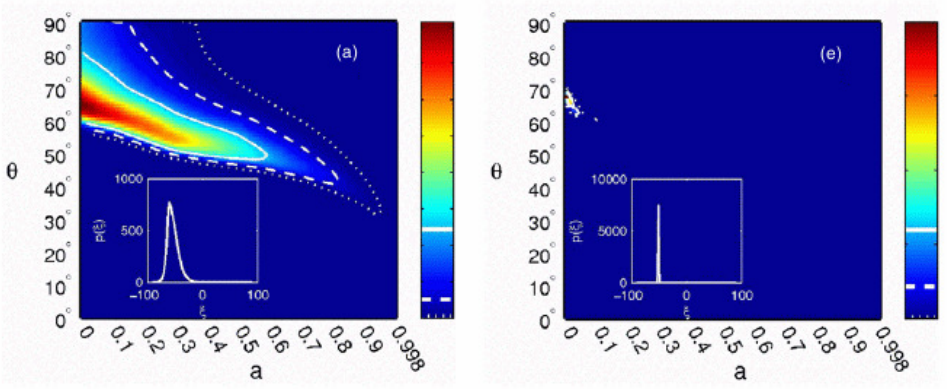
Wang et al 2014



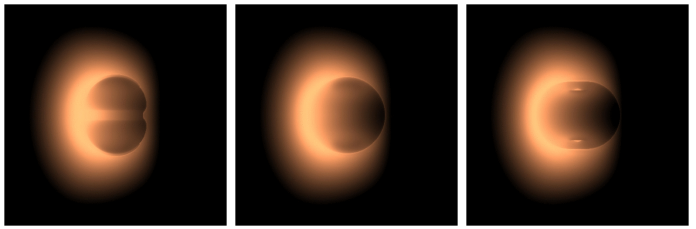
Li, Morris, Baganoff 2013

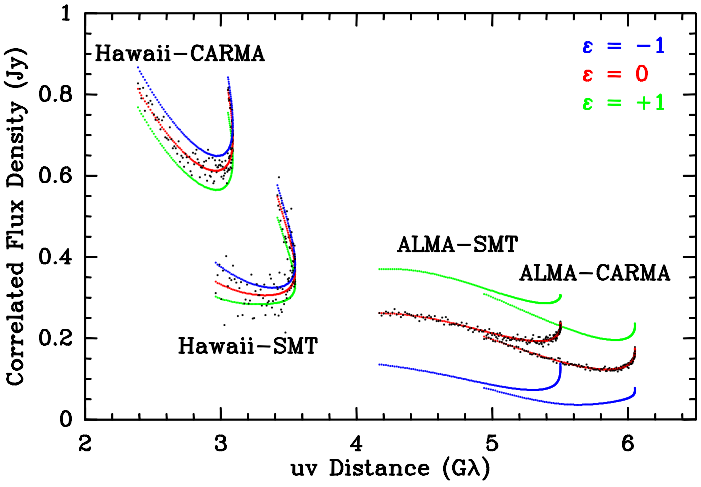
Fundamental Physics with Sgr A*

Constraints on Black Hole Spin from images
Broderick et al 2011

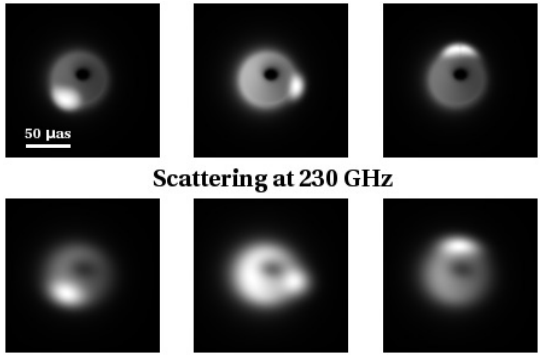


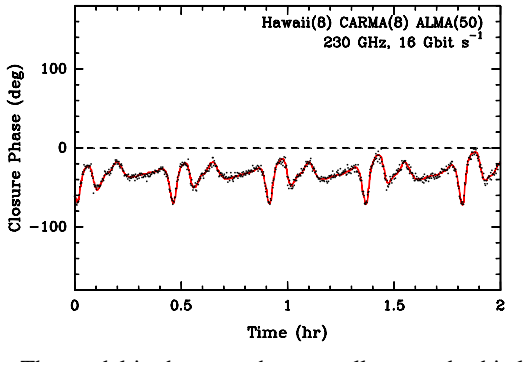
Violations of the No-Hair Theorem
Introduction of Quadrupole Moment
Psaltis and Broderick



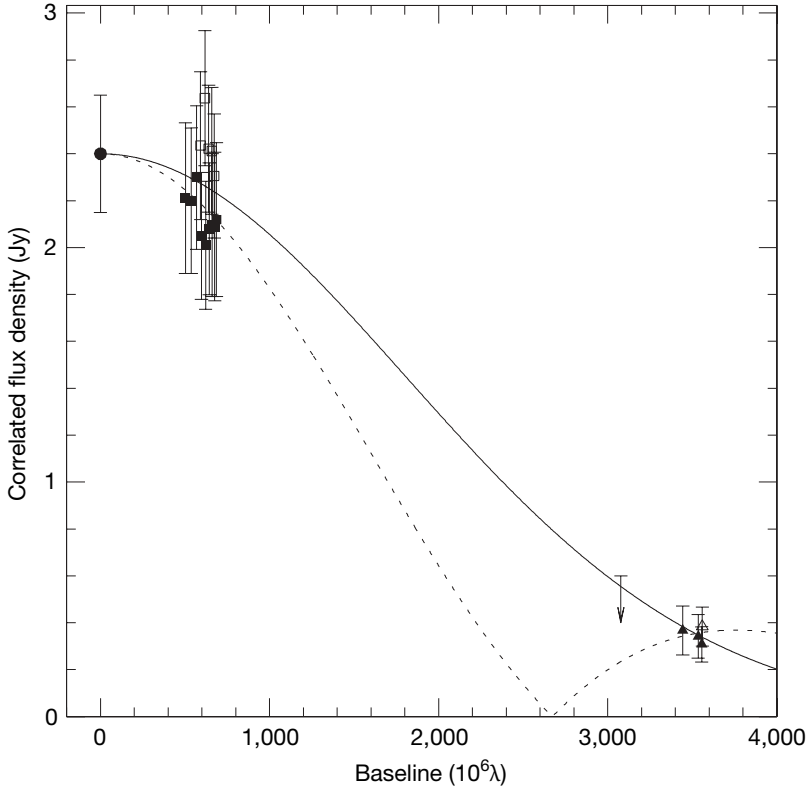


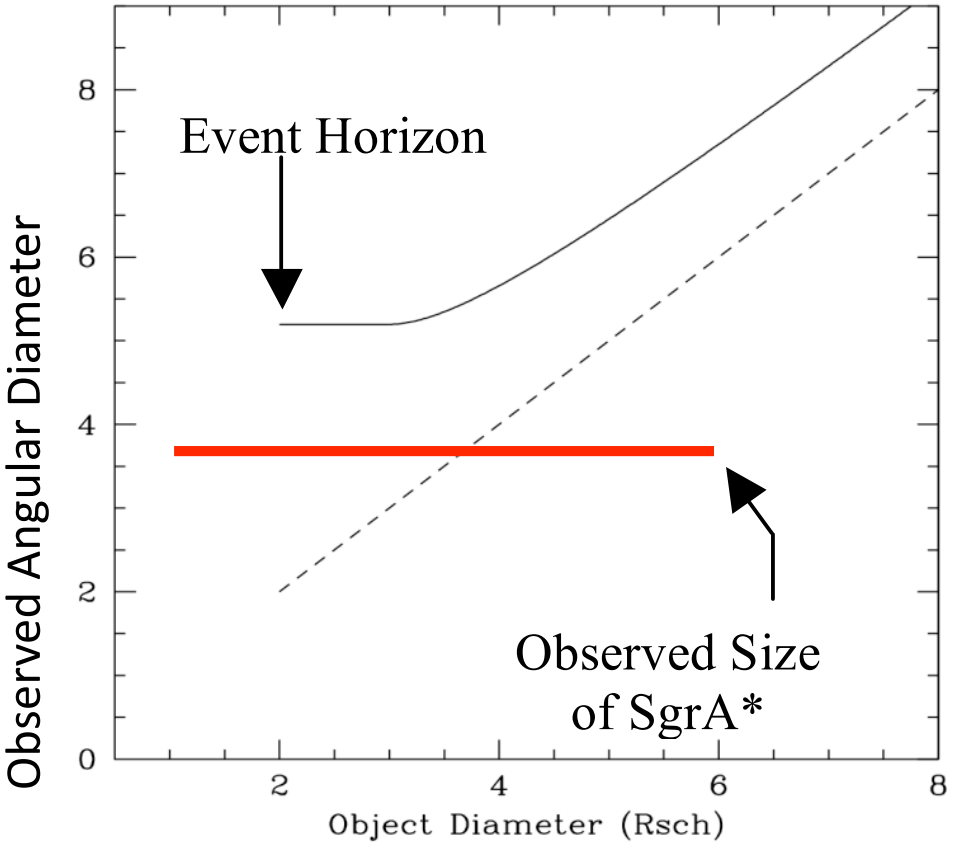
Constraints on Geometry/Mass from Orbiting Hot Spots
Doeleman et al 2009



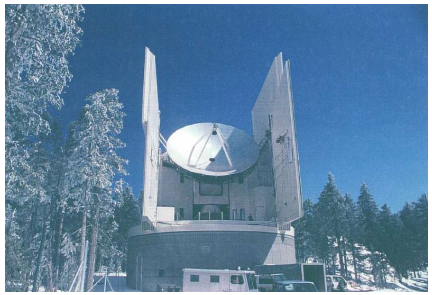


MM VLBI Imaging of Sgr A*

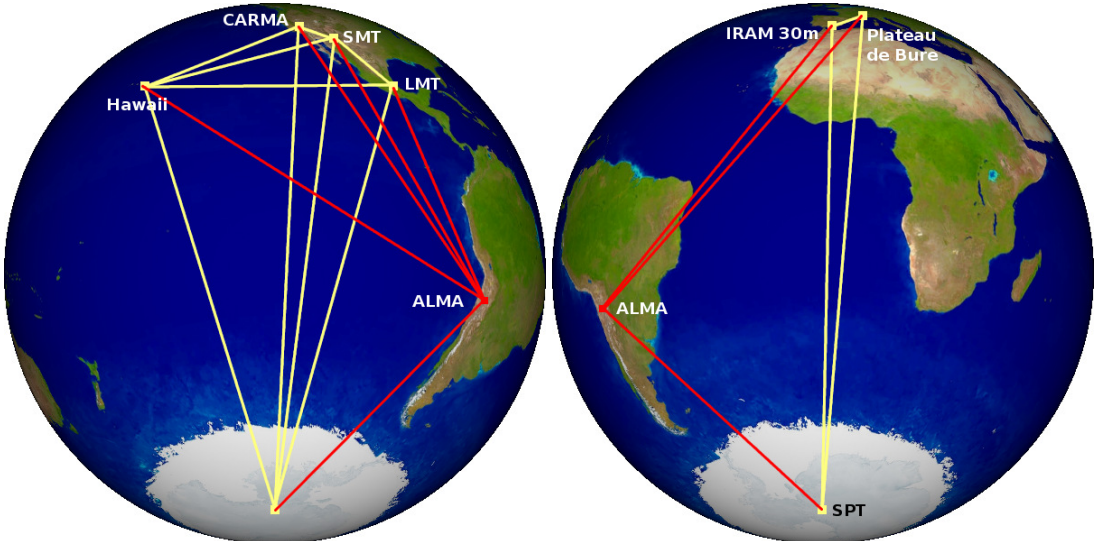


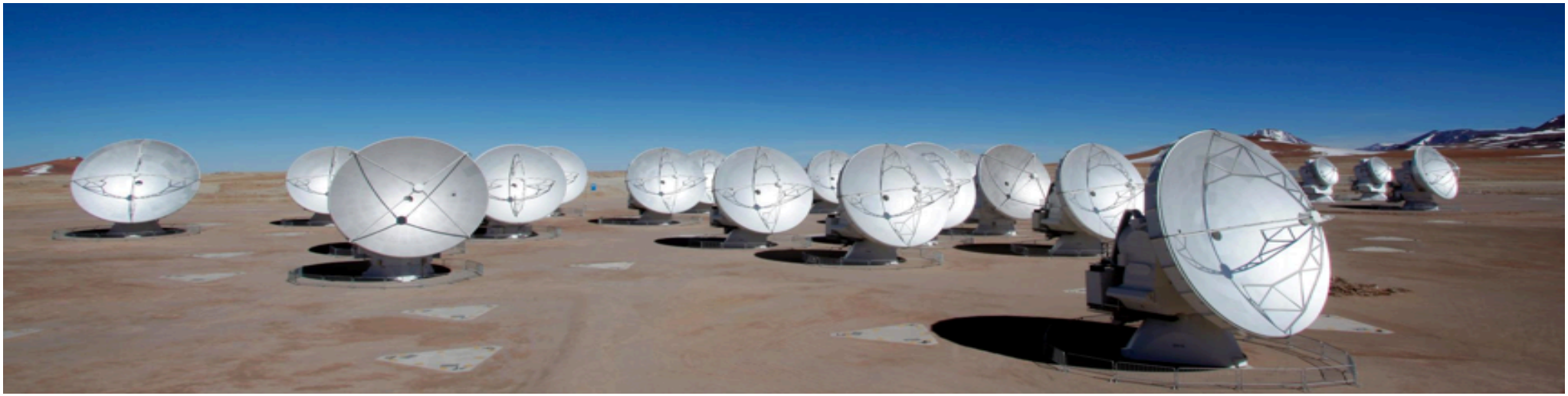


Doeleman et al 2008



The Event Horizon Telescope





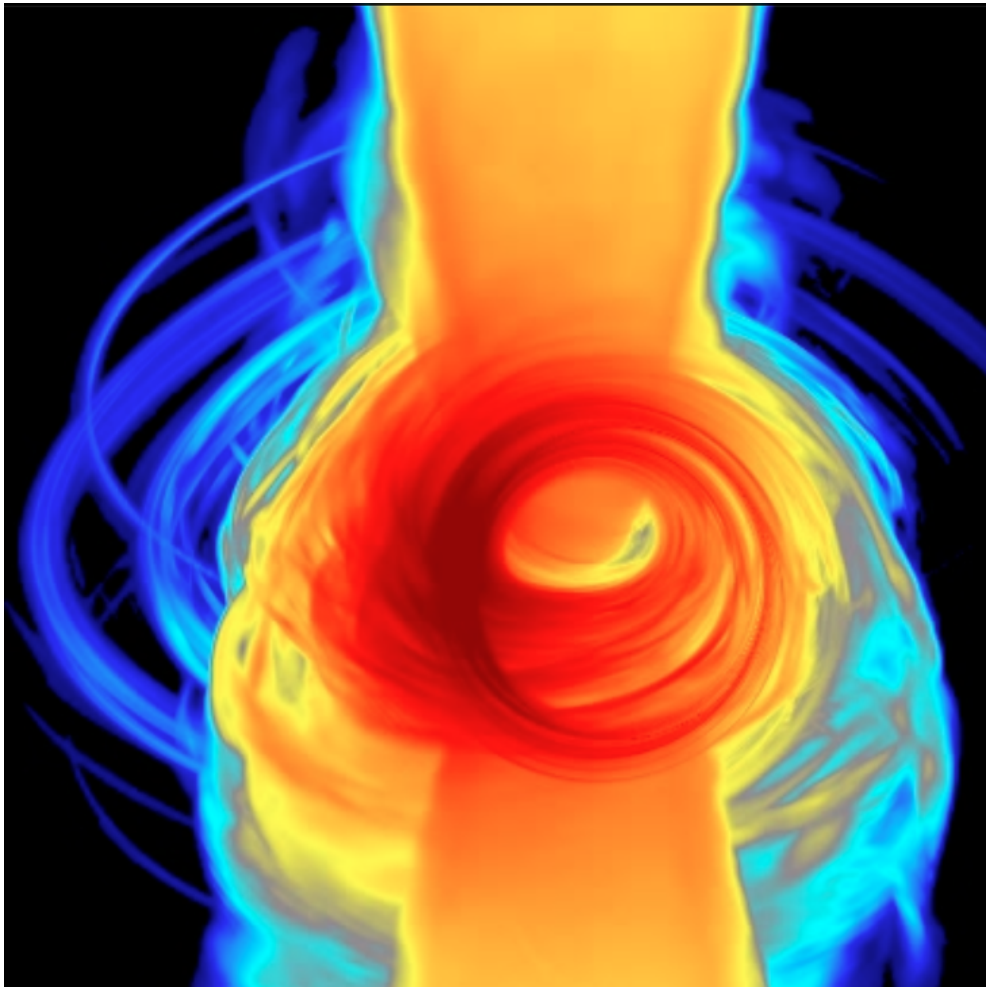
2017 EHT Campaign

- Eight stations
  - PV, LMT, ALMA, APEX, SMT, JCMT, SMA, SPT
  - Most sensitive, most uv-complete experiment
- Correlation and analysis underway
  - Fringes detected to all stations
  - Results in 2018
- Over 200 members of EHTC on 6 continents

Akiyama Talk!

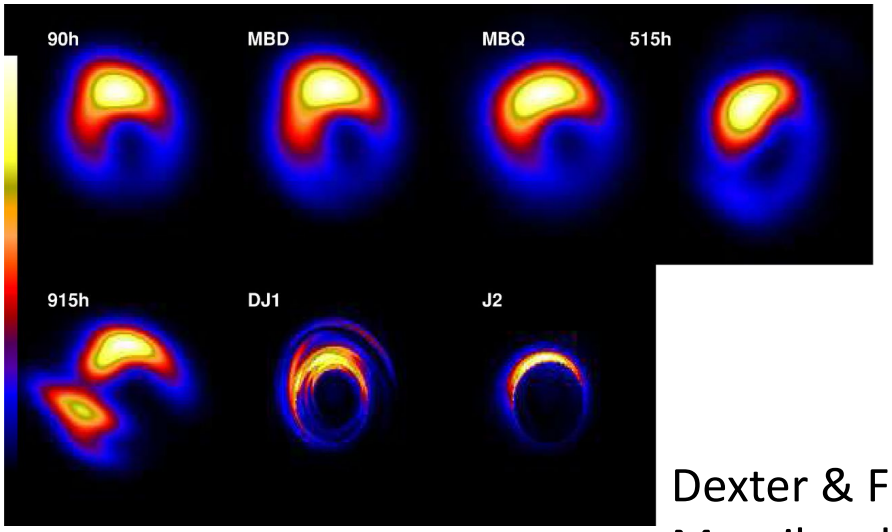
The Astrophysical Model & EHT Imaging

- Mode of accretion: Bondi, ADAF, CDAF, RIAF
- 3D Magnetohydrodynamics
- General Relativity Inflow: Accretion Outflow: Jets BH – MHD interface (ISCO)
- Microphysics: Heating & cooling of particles
- Radiation Transport
- Presence of a jet

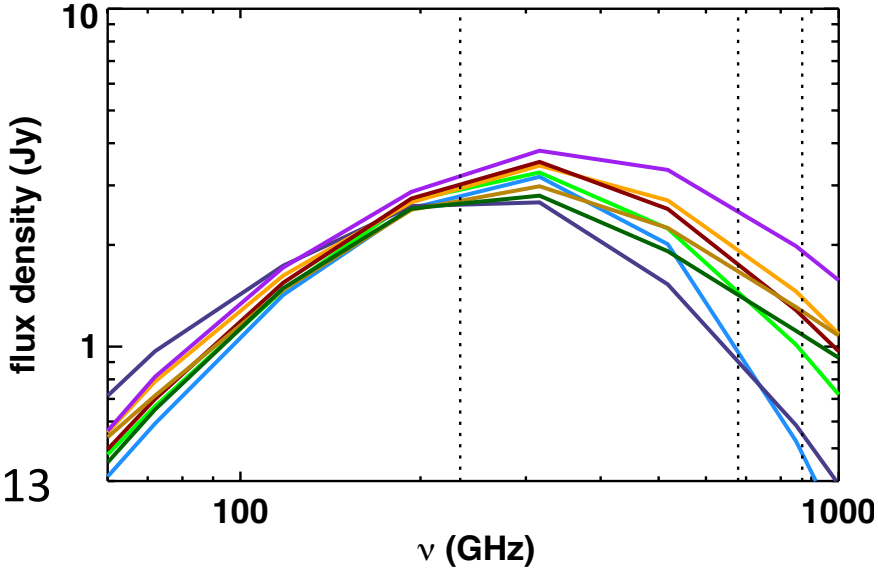


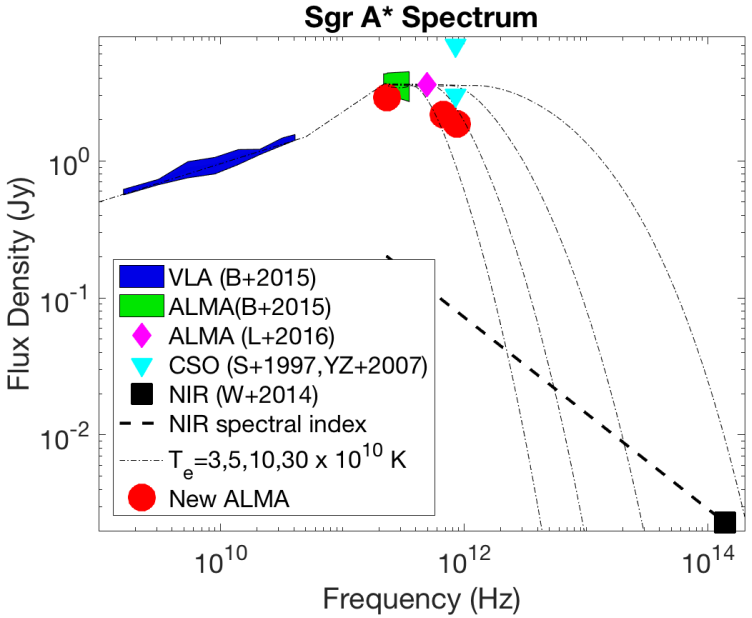
(Gammie et al.)

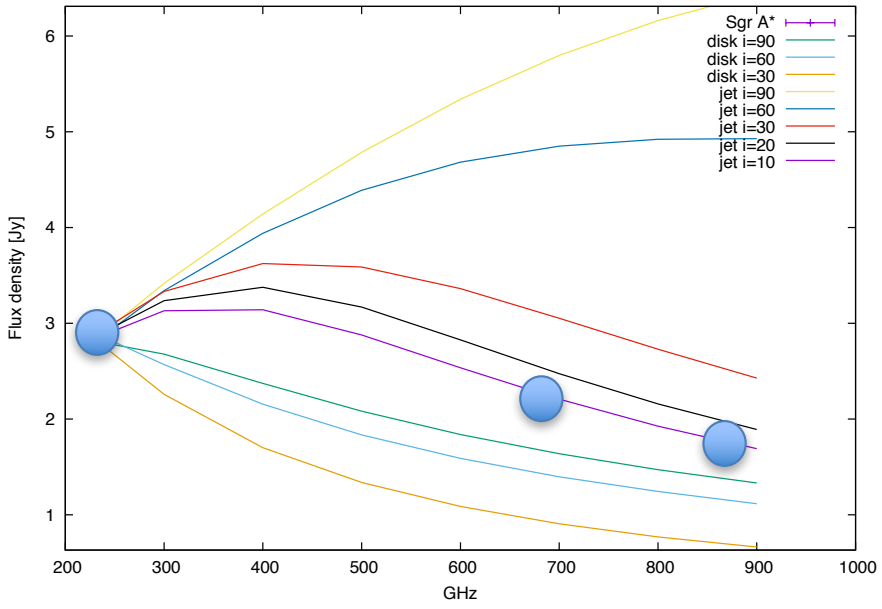
Millimeter/Submm Spectrum



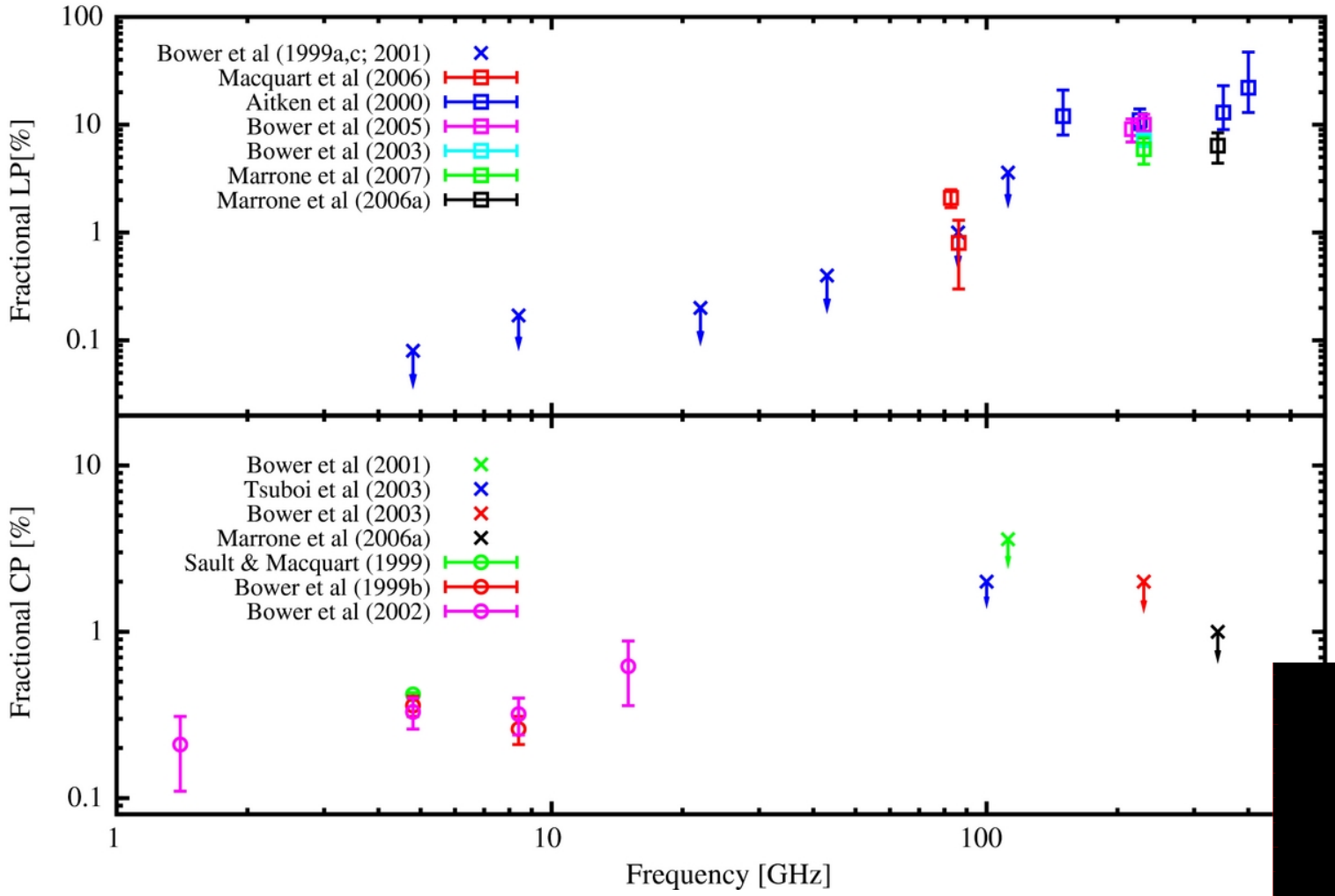
Dexter & Fragile 2013
Moscibrodzka et al

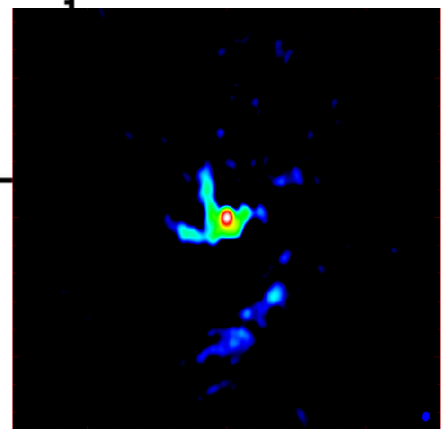






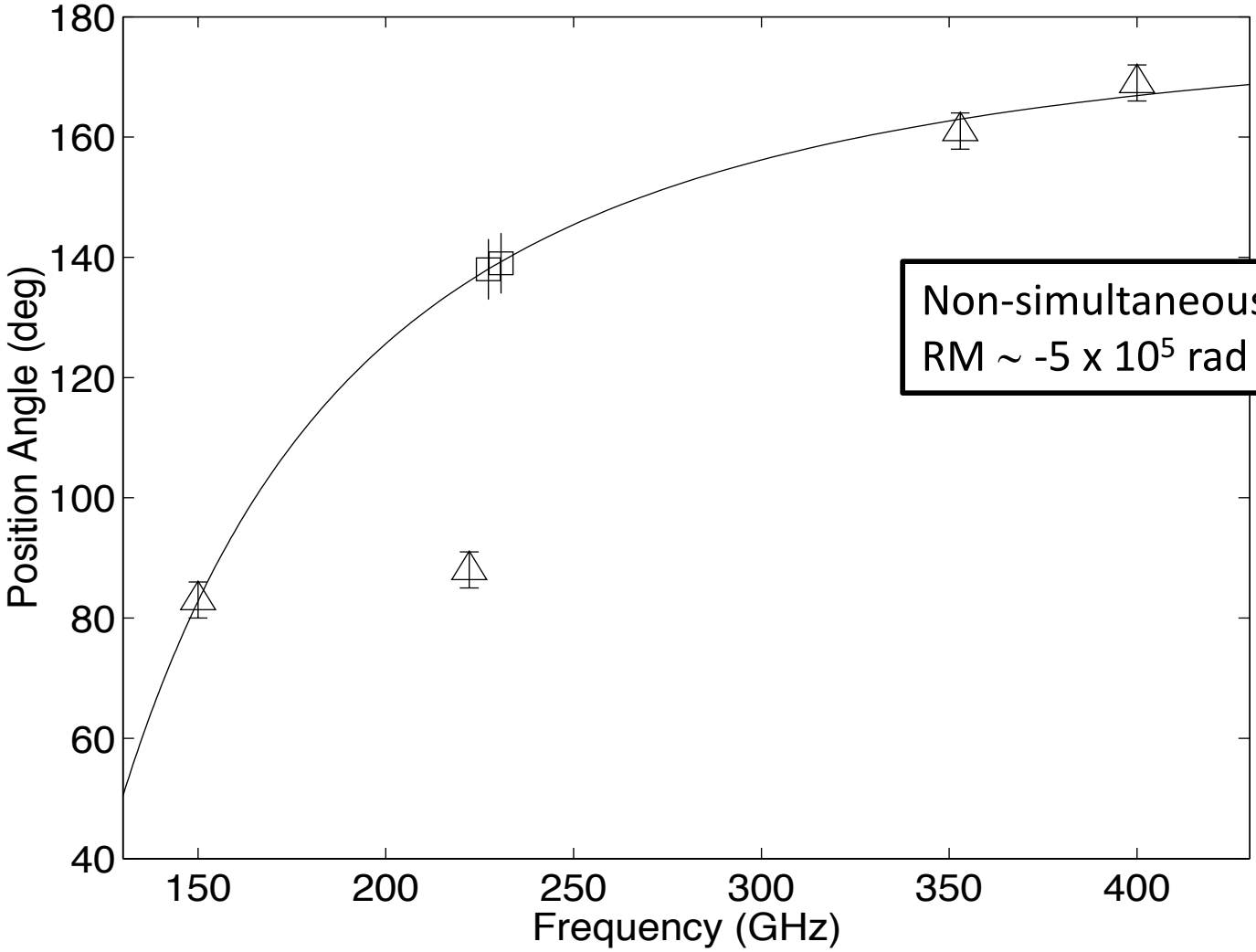
Polarization Fraction of Sgr A*





Munoz et al 2011

Rotation Measure for Sgr A*

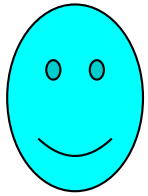


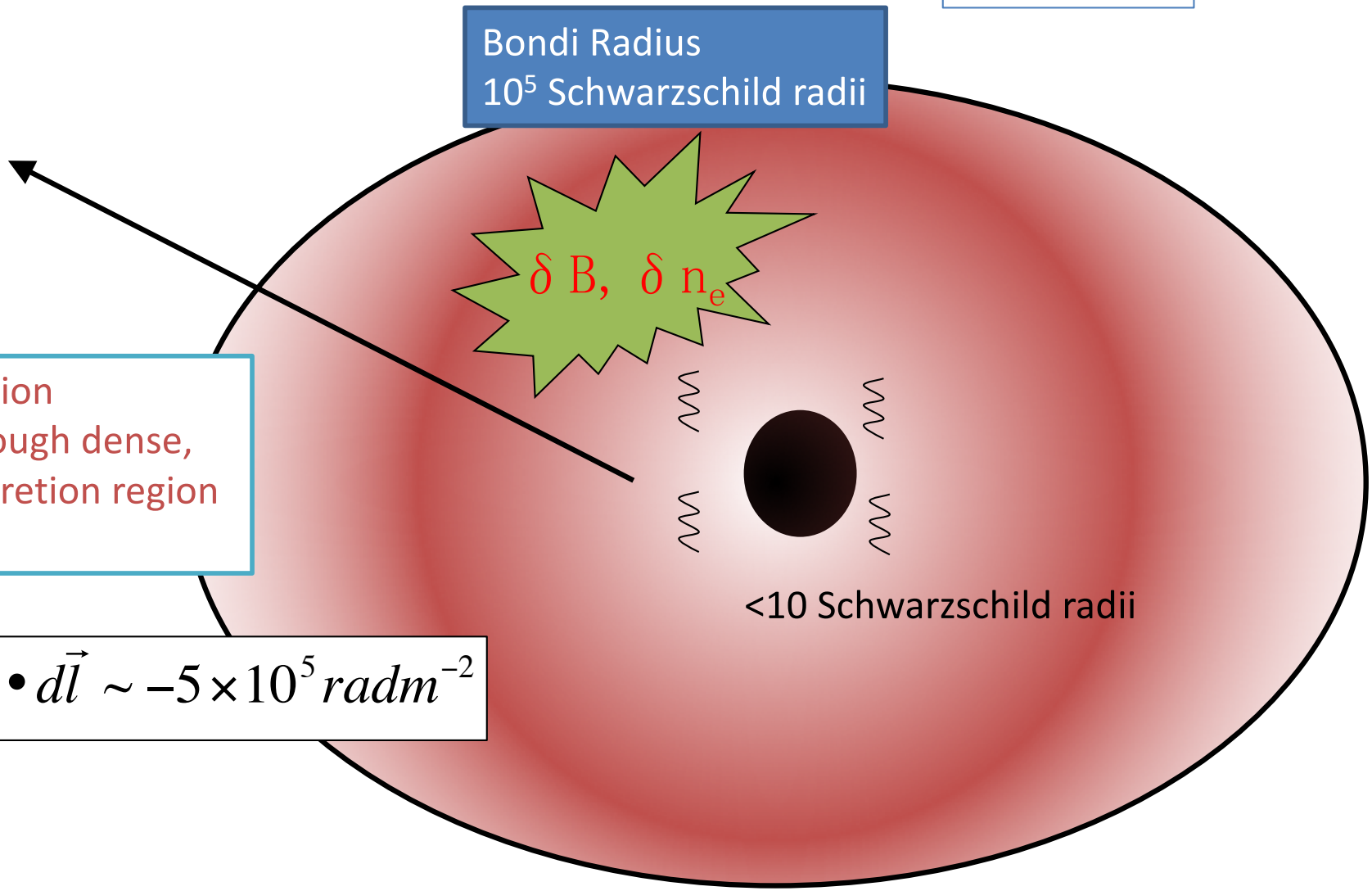
Non-simultaneous data
RM ~ -5 x 10^5 rad m^{-2}

Bower et al 2003

RM Originates in the Accretion Flow

Sgr A*





Polarized radiation propagates through dense, magnetized accretion region

$$RM \alpha \int n_e \vec{B} \bullet d\vec{l} \sim -5 \times 10^5 \, rad m^{-2}$$

RM Constrains Accretion Rate → $M_{dot} \sim 10^{-8 \pm 1} M_{sun}\ y^{-1}$

Bower et al 2003, Marrone et al 2006

Time-Dependent Accretion Simulations Predict RM Changes

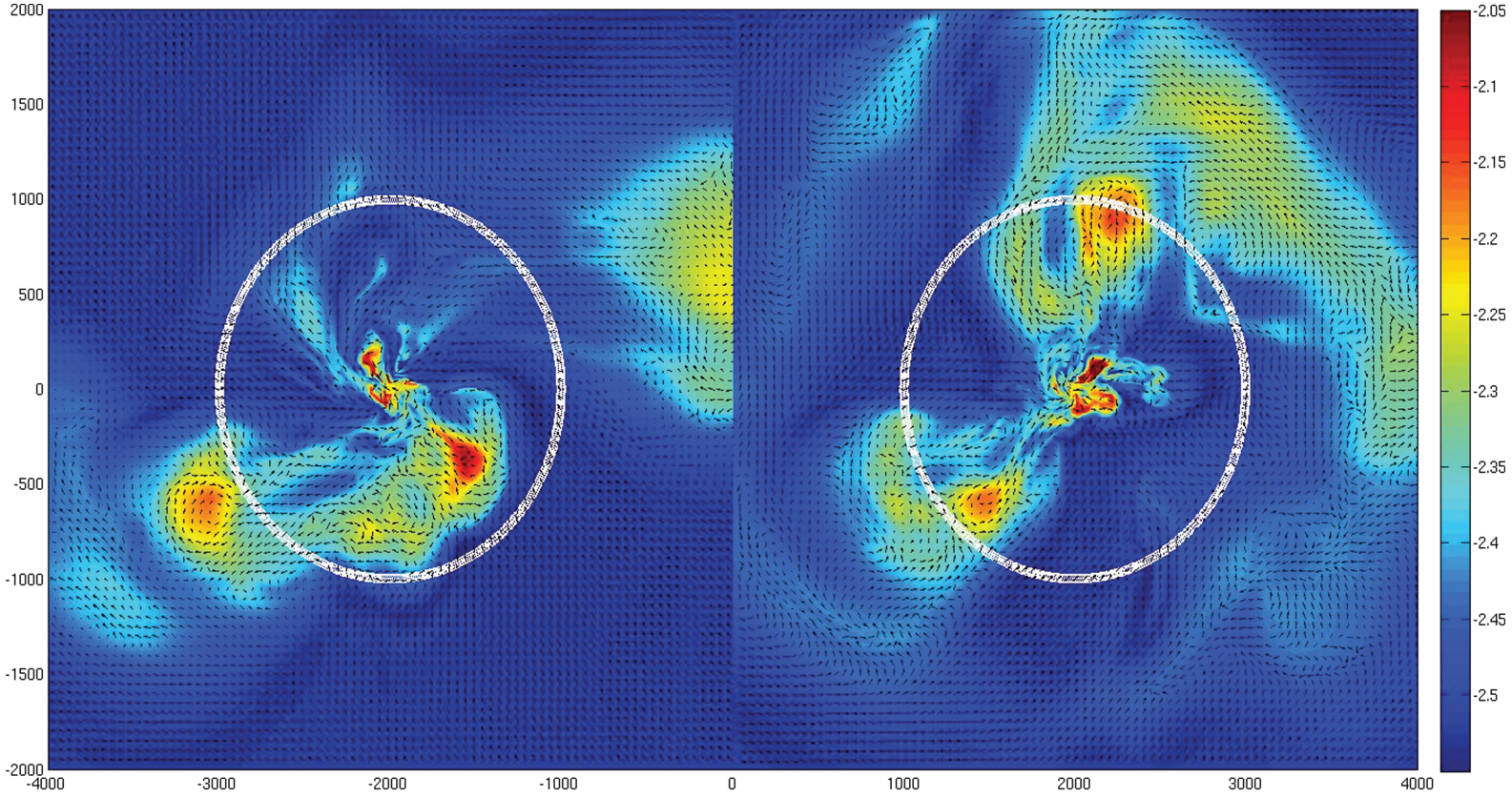


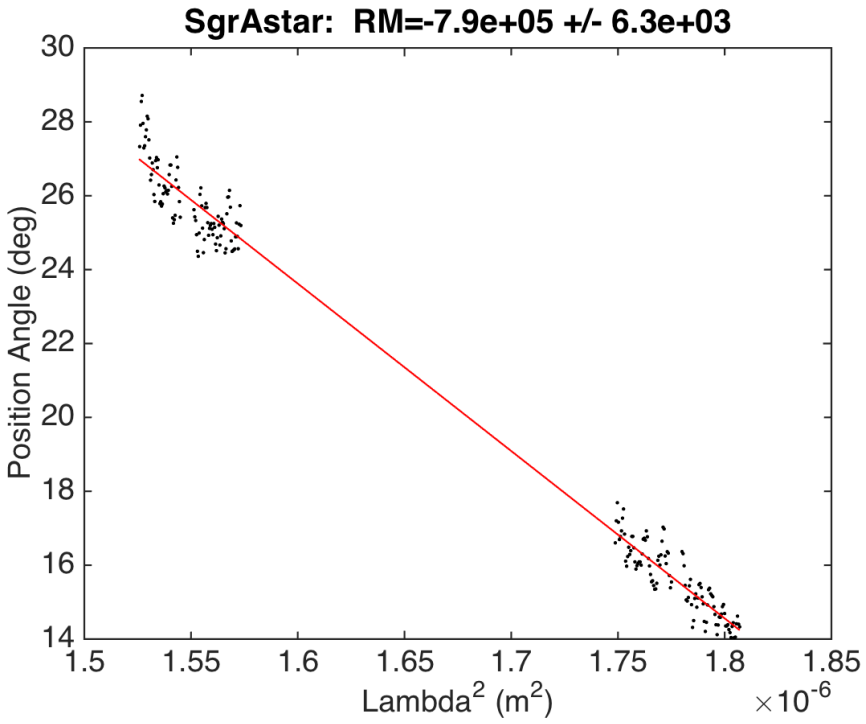
Figure 1. 2D slice of the simulation for 600^3 box at 15 Bondi times. Colour represents the entropy, and arrows represent the magnetic field vector. The right-hand panel is the equatorial plane (yz), while the left-hand panel a perpendicular slice (xy). White circles represent the Bondi radius ($r_B = 1000$). The fluid is slowly moving, in a state of magnetically frustrated convection. A movie of this flow is available as Supporting Information with electronic version of this article (see Appendix C for a description).

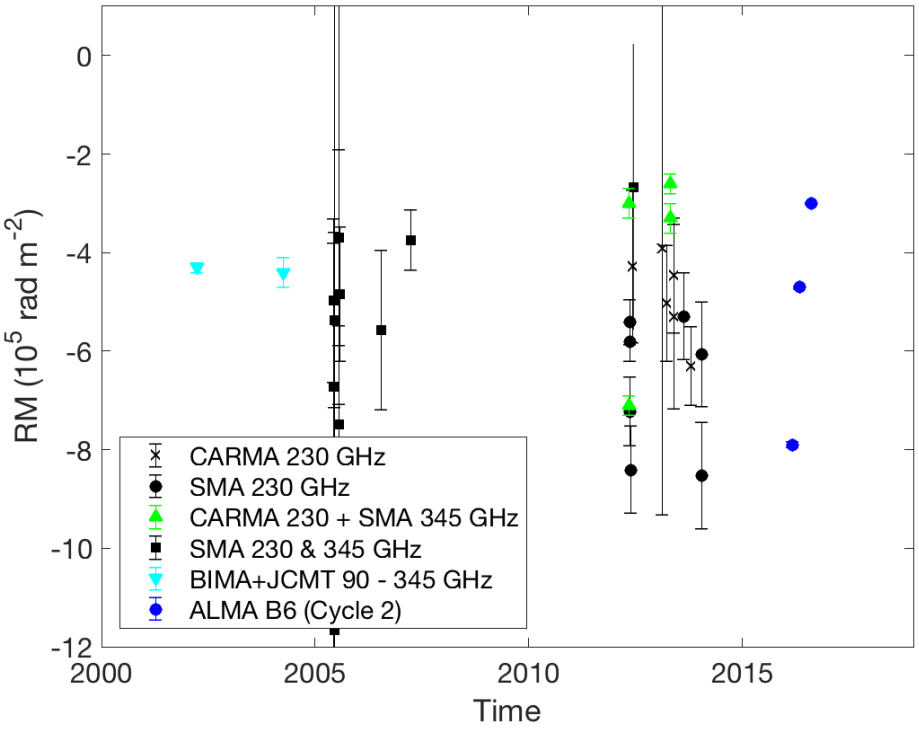
Pang, Pen, et al 2011

ALMA Sgr A*Polarization Campaign

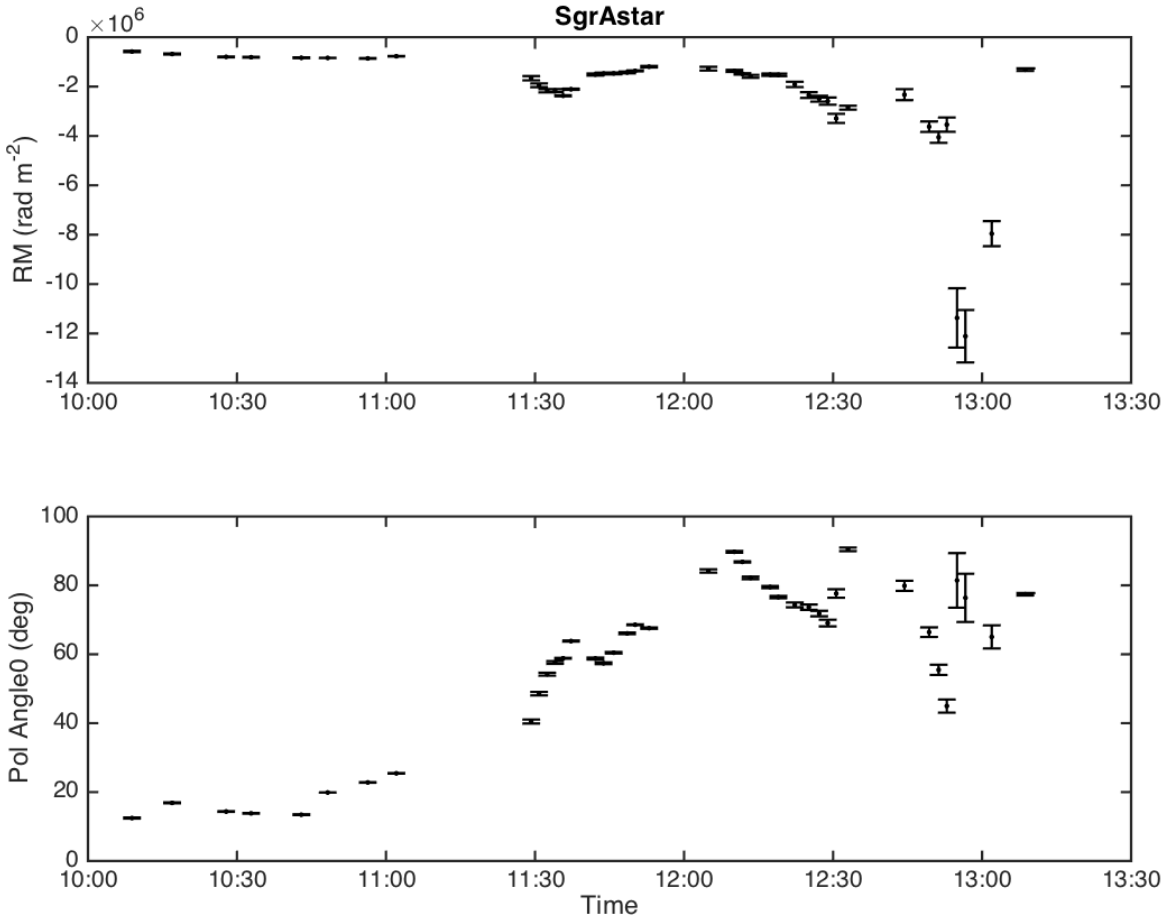
- Band 6 = 230 GHz
  - 4 spectral windows @
- Three Epochs
  - 03 March 2016: 3 hours
  - 03 May 2016: 3 hours
  - 13 August 2016: 8 hours
- Goals
  - Precise measurement of RM
  - Time variations in RM
  - Non-lambda^2 effects
  - Short-time scale variations in polarization

Time Variable Rotation Measure

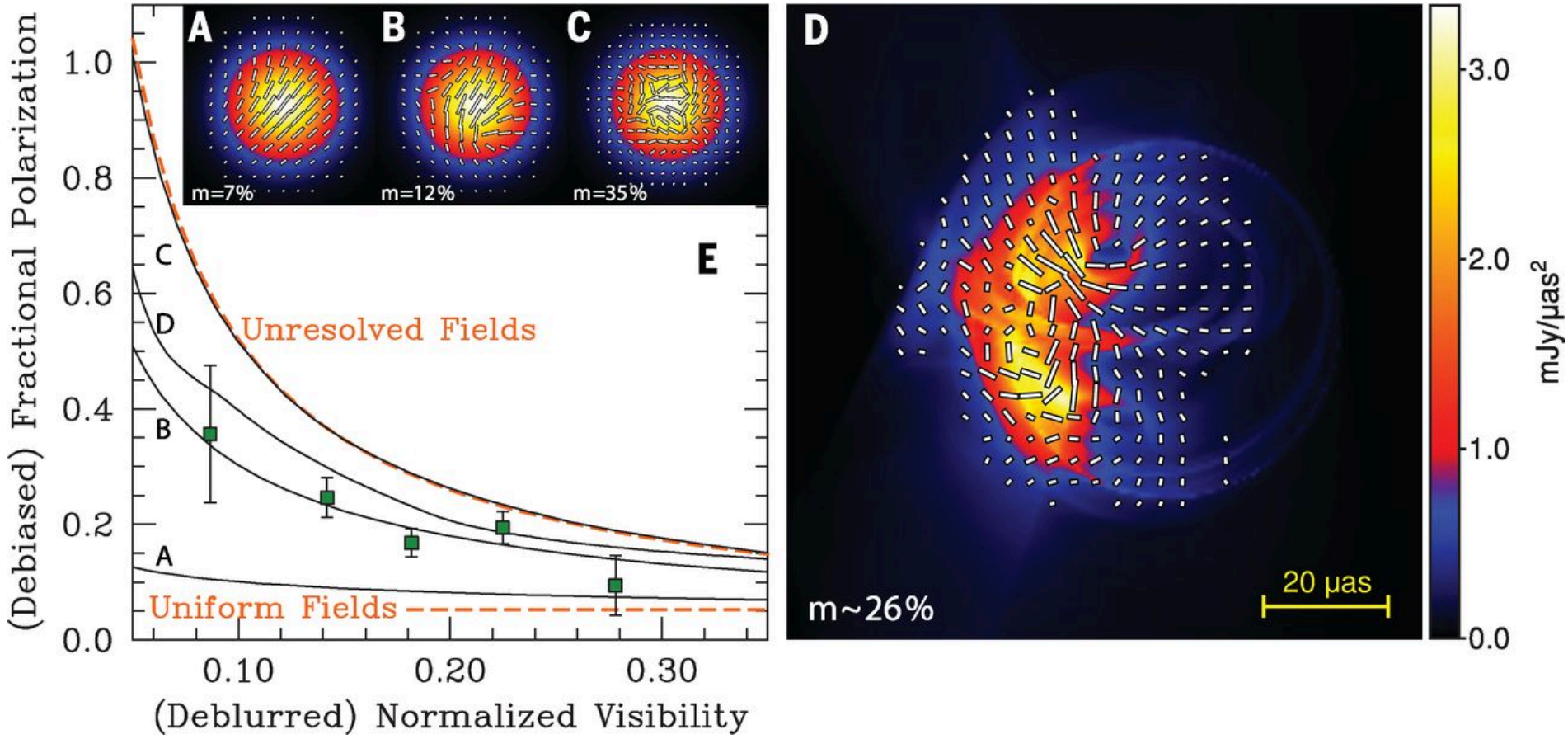




Short Timescale Variable RM

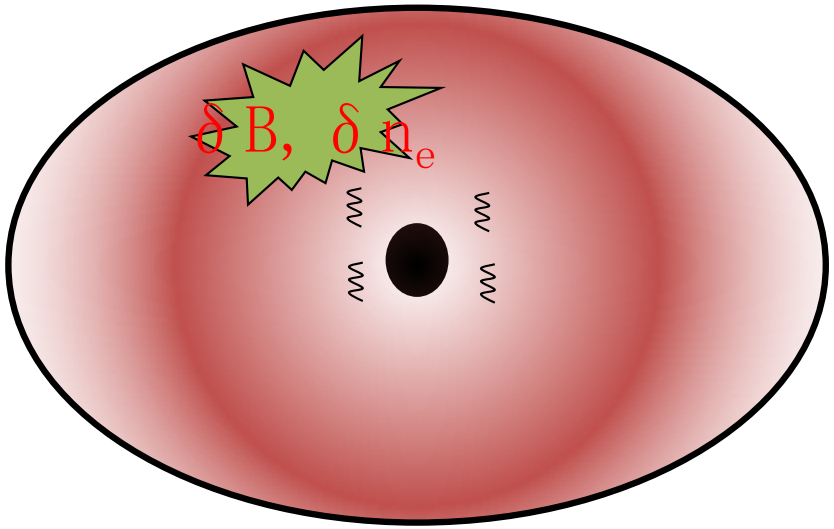


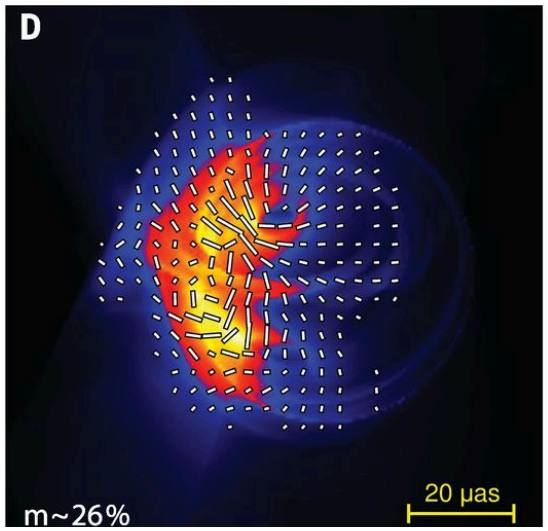
EHT Polarization of Sgr A*



Johnson et al 2015

Polarization Interpretation





- Long-term stability with month-scale variability
- Extreme short-term variations
- Complex, time variable intrinsic polarization structure
- Mixed nonthermal and thermal electrons
- Does a model of a distant, independent Faraday screen hold-up?

The G2 Gas Cloud Event

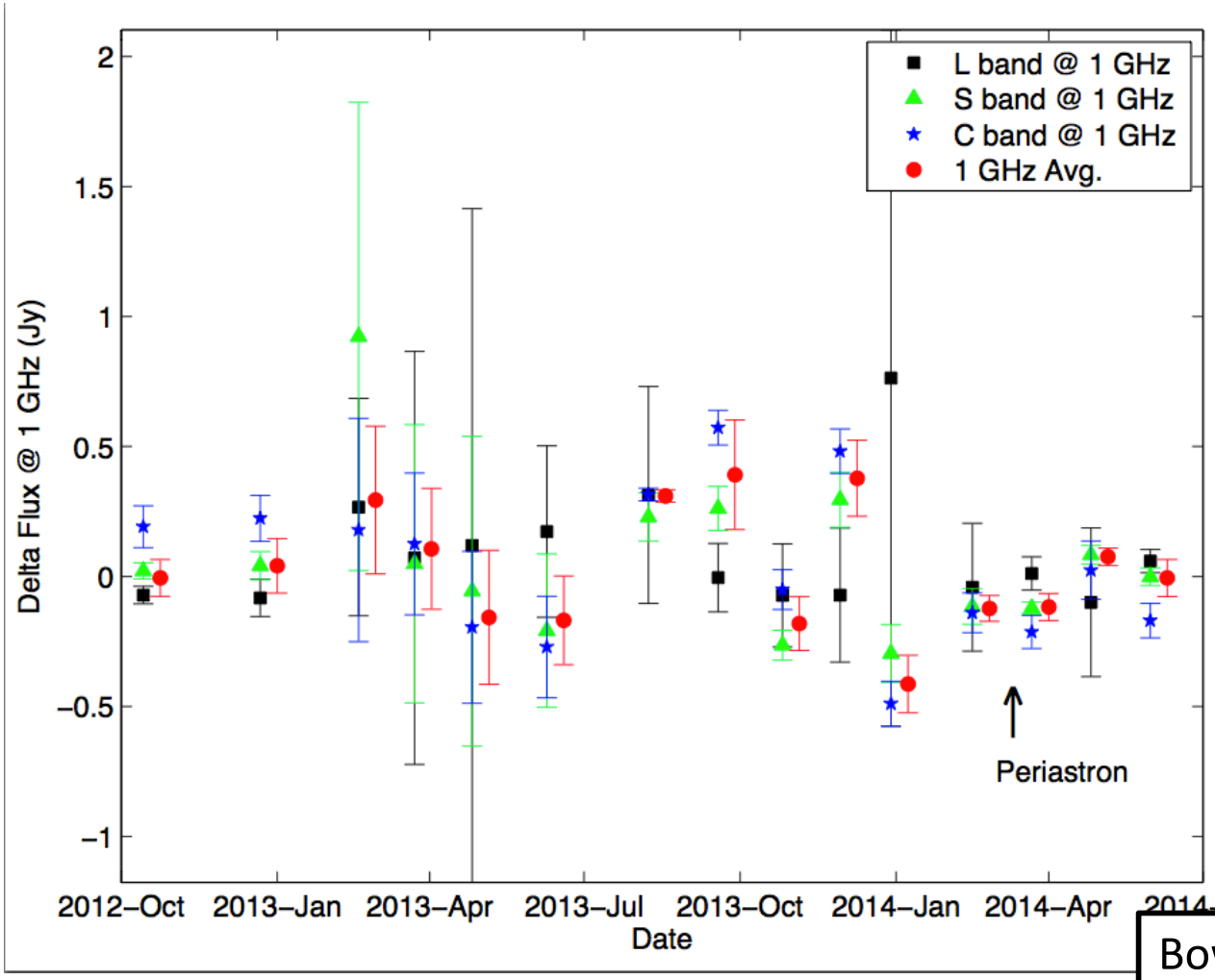
A gas cloud on its way into the super-massive black hole in the Galactic Centre

S. Gillessen, R. Genzel, T. Fritz, E. Quataert, C. Alig, A. Burkert, J. Cuadra, F. Eisenhauer, O. Pfuhl, K. Dodds-Eden, C. Gammie, T. Ott

Nature, Dec. 2011

Simulation by: M. Schartmann, A. Burkert, C. Alig, S. Gillessen, R. Genzel
using PLUTO 3.1.1 (Mignone et al. 2007)

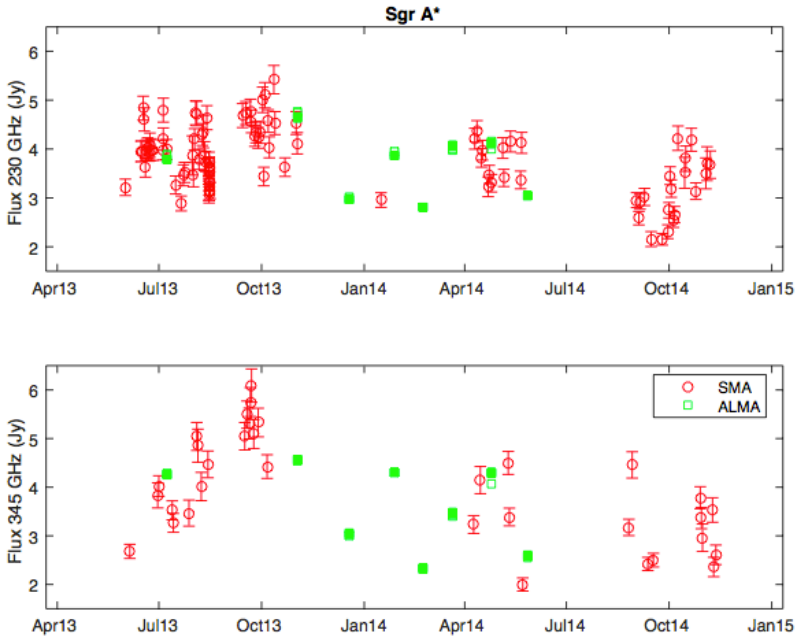
No Bowshock

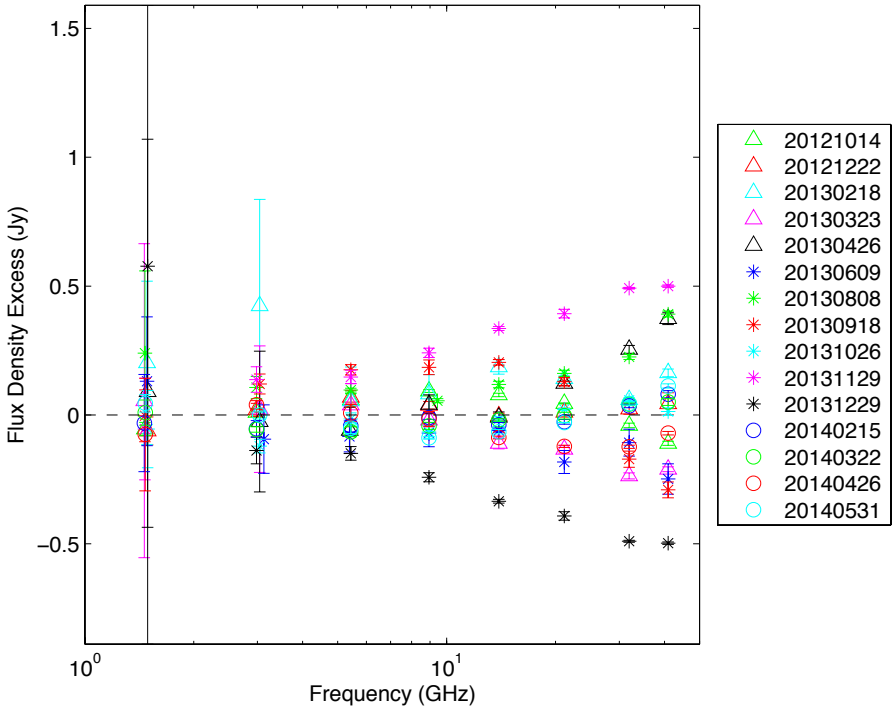


→ Size < 2 x 10^{29} cm^2 *or* Error in Accretion Flow Model

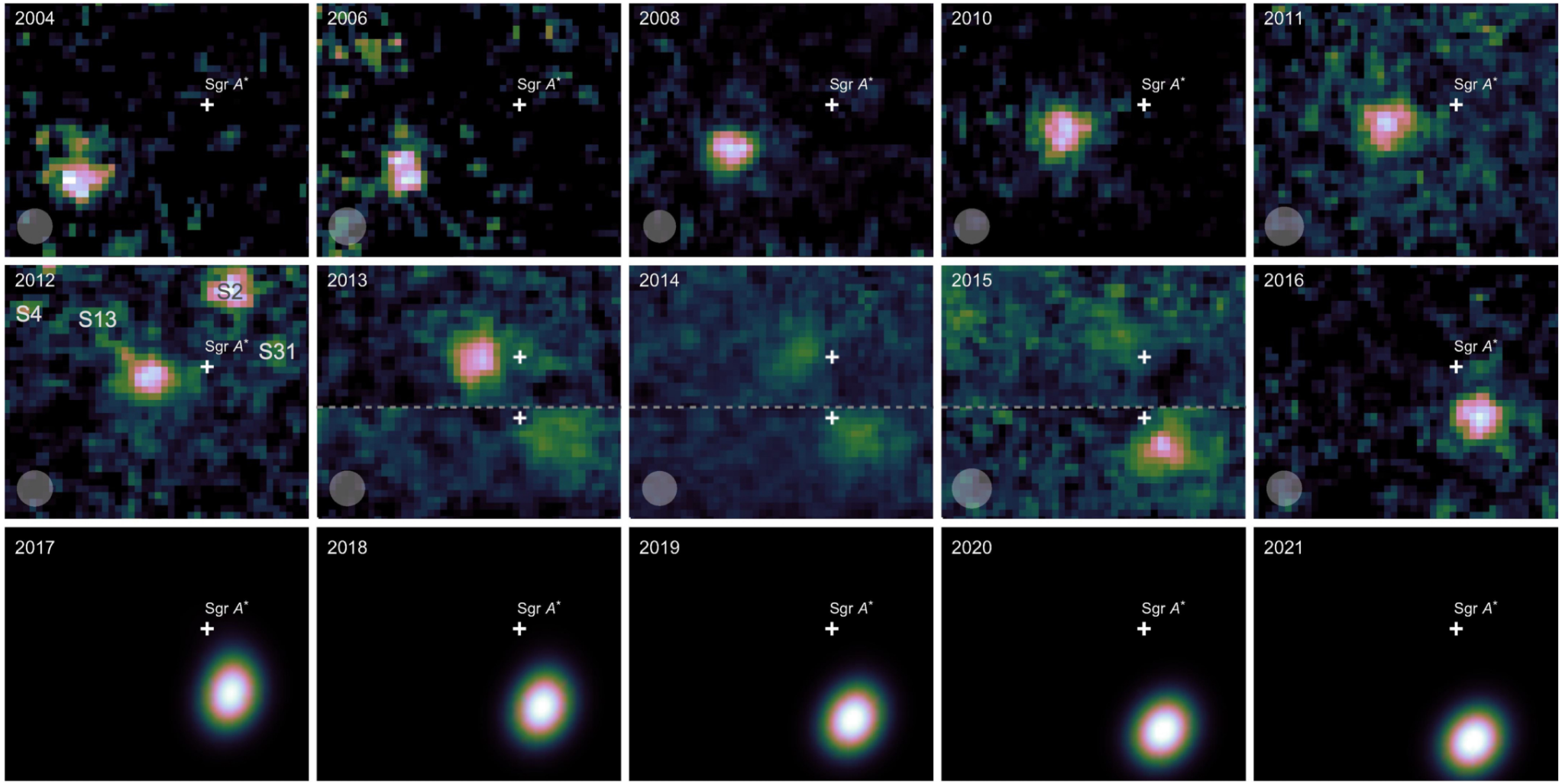
Bower et al 2015
Narayan et al 2013
Sadowski et al 2013

No Enhanced Accretion



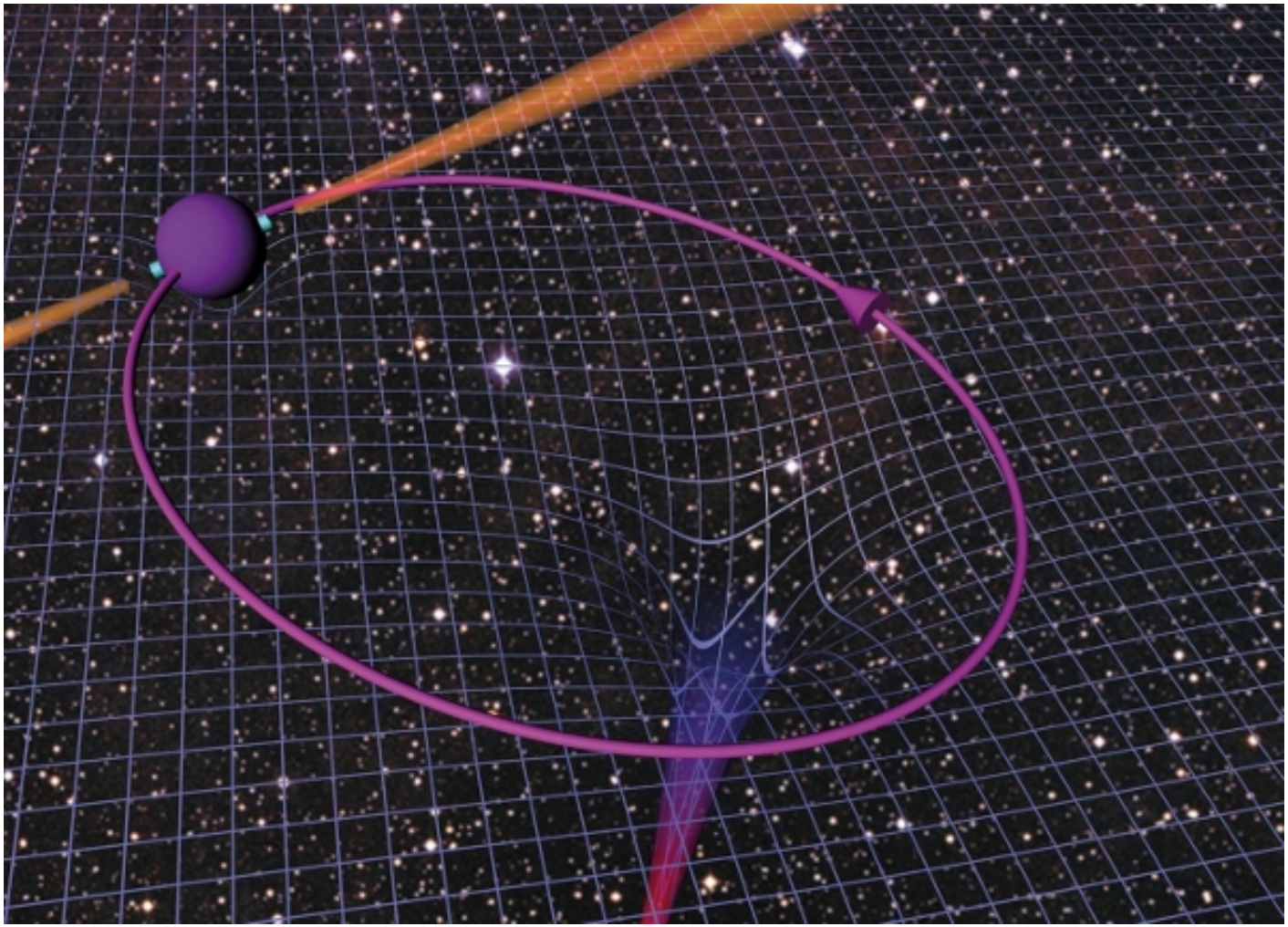


G2 Cloud Survives Periastron



Br gamma: Plewa et al 2017

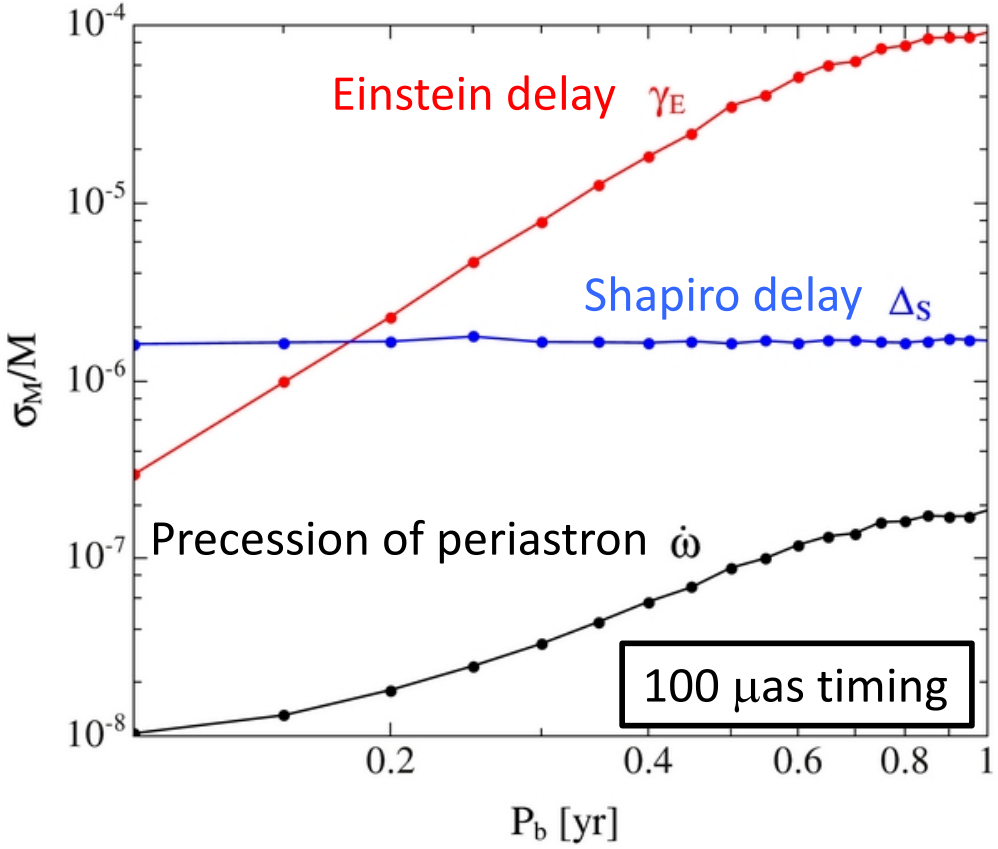
A Pulsar in Orbit Around a BH



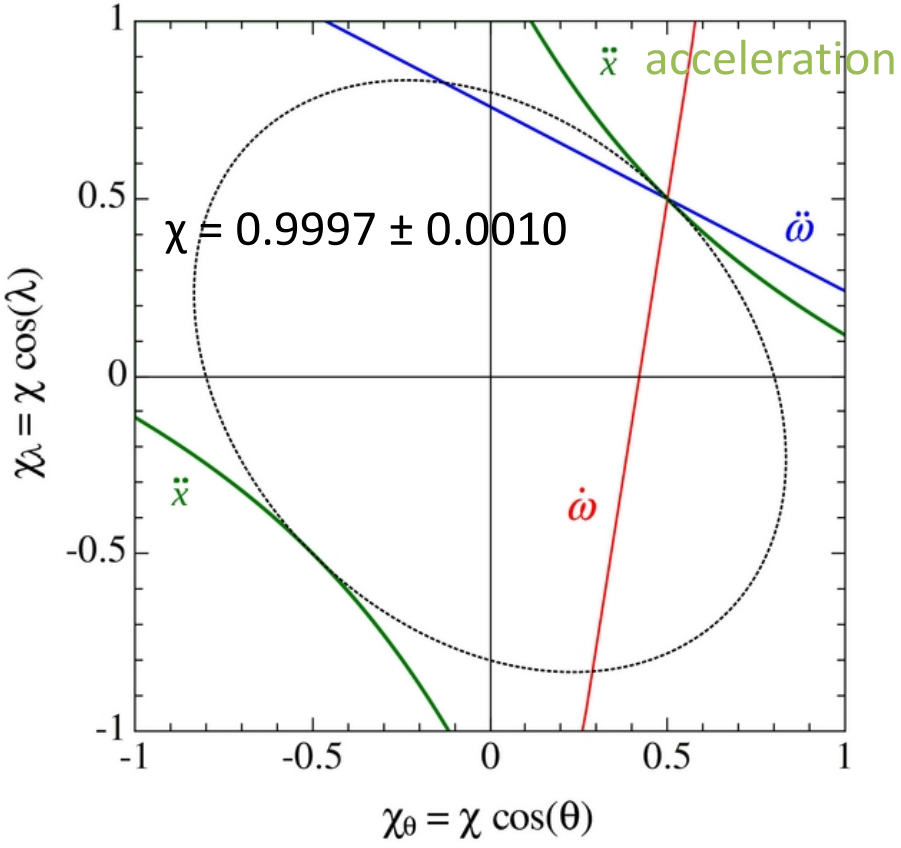
Kramer et al

Using Pulsars to Measure Spacetime Around Sgr A*

Black Hole Mass



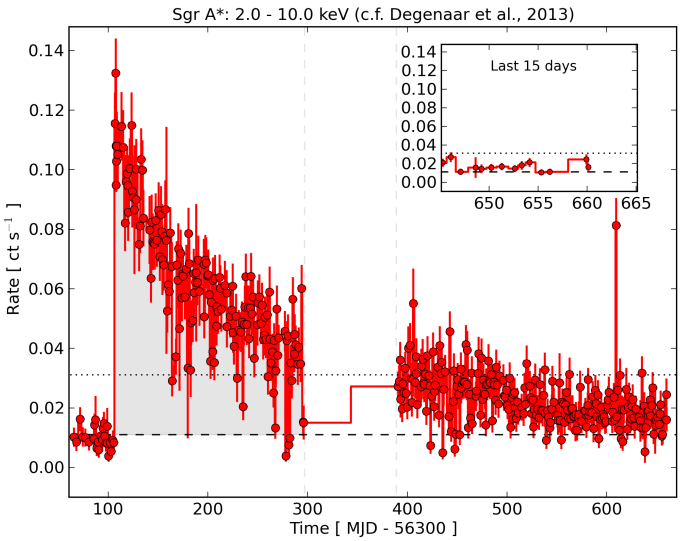
Black Hole Spin



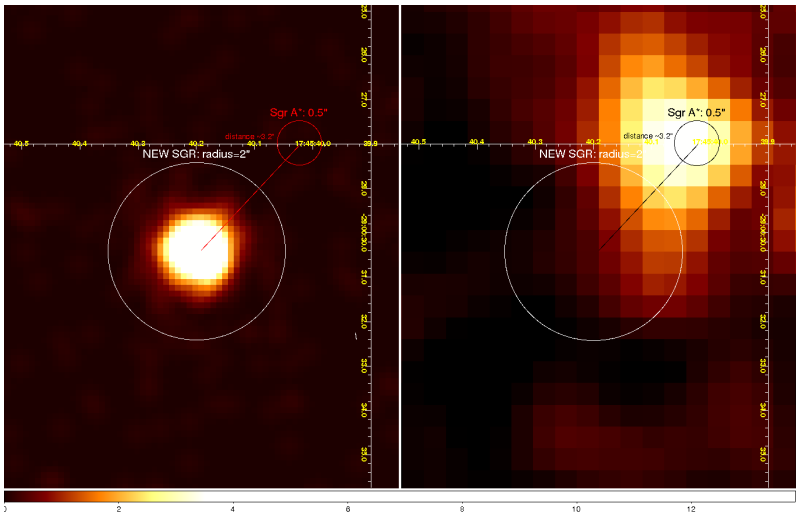
Liu et al 2012

Galactic Center Magnetar Discovery

X-Ray Burst



X-ray Localization: ~2” to Sgr A*



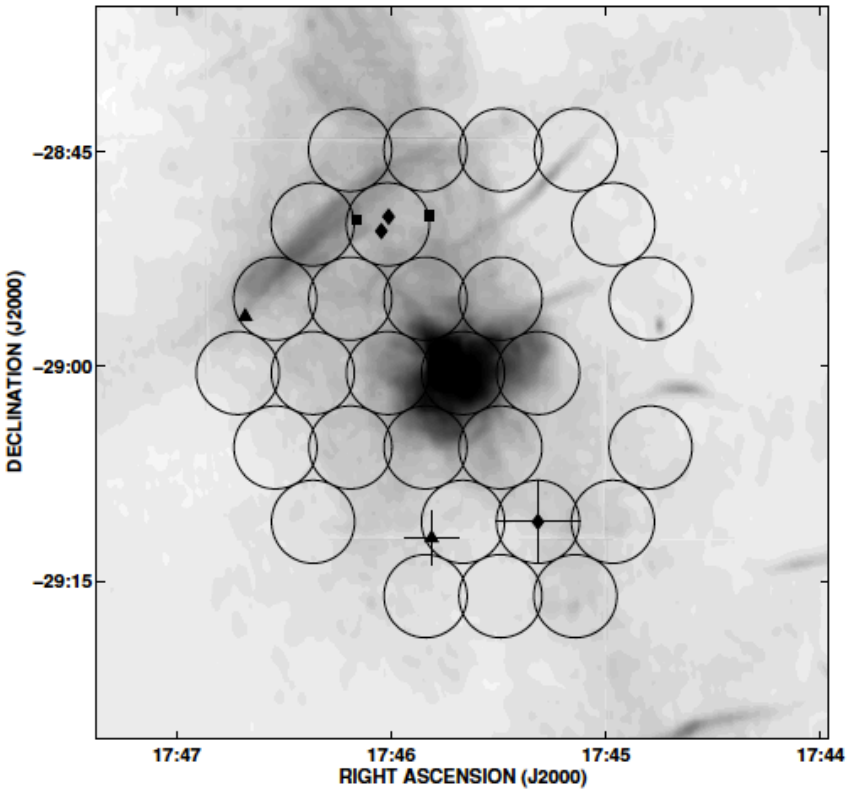
Degenaar et al. 2013
Kennea et al. 2013

Rea et al. 2013

SGR J1745-29

2” ~ 0.1 pc

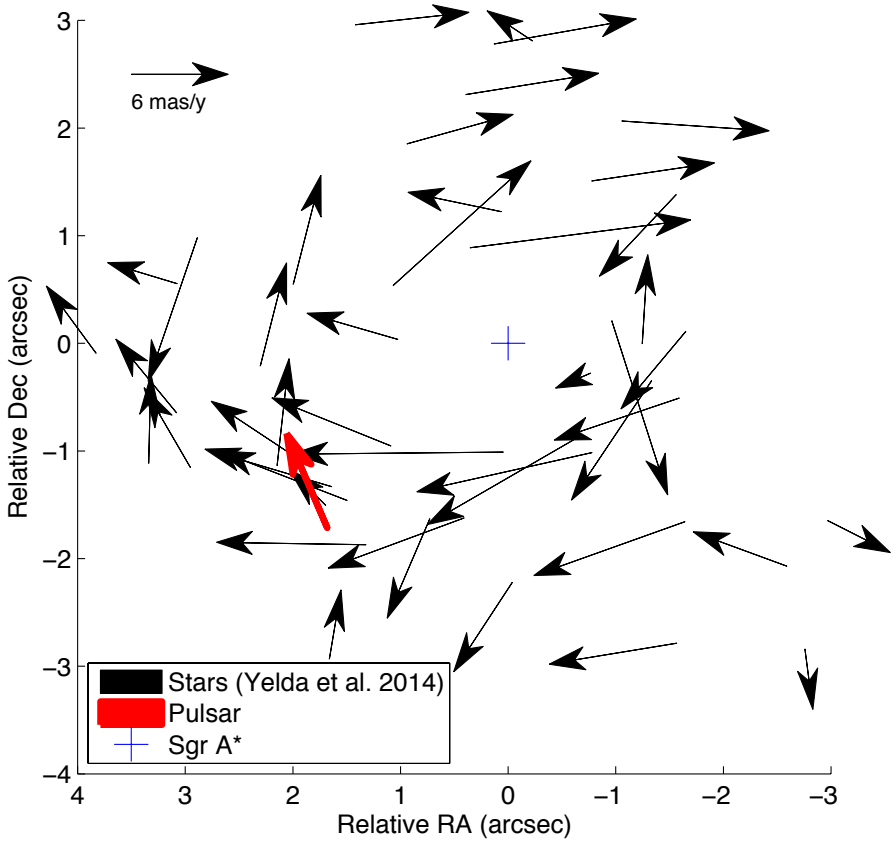
Known GC Pulsars



PSR	P (ms)	B (10^{12} G)	DM (pc cm^{-3})	τ_{sc} (2 GHz; ms)
1746-2850I	1077	38	962	100
1746-2850II	1478	3	1456	145
1745-2910	982	---	1088	---
1746–2856	945	4	1168	---
1745–2912	187	---	1130	144

Johnston et al. 2006
Deneva et al. 2009

The GC Pulsar Likely Originates in the Clockwise Stellar Disk



- V_{proj}=240 +/- 3 km s^{-1}
- R_{proj}=0.097 pc
- P>700 y

- Acceleration measures |z| and would conclusively demonstrate that the PSR is bound to Sgr A*

Arches cluster

Cavity excavated by heavy stars

Milky Way centre

Quintuplet cluster

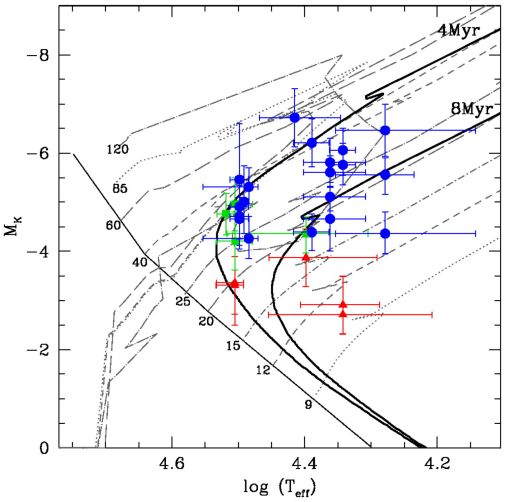
HST & Spitzer: Wang, Stolovy et al 2015

- WR+OB Stars
- T~2.5 – 5.8 Myr
- M~10^4 M_{sun}

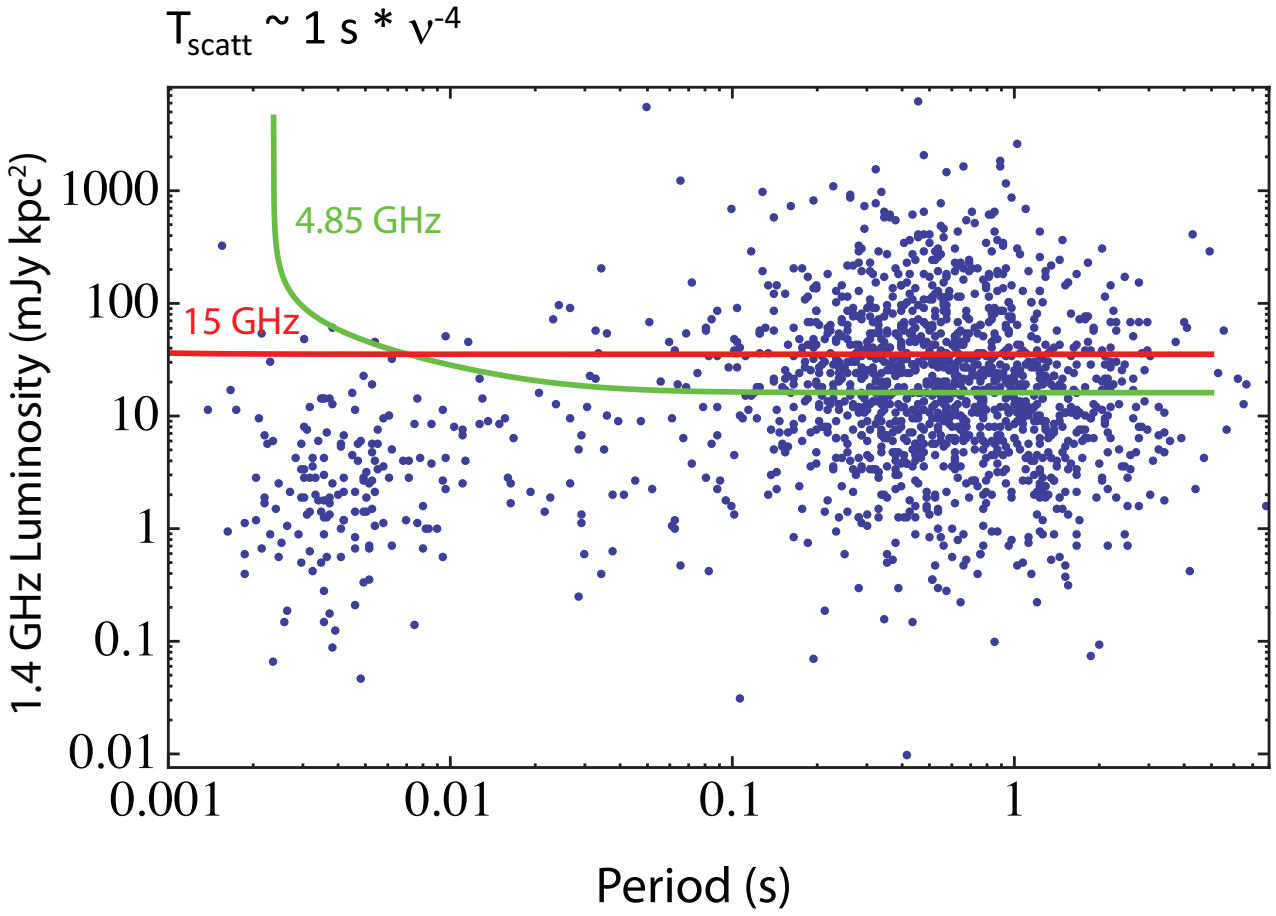
Paumard et al 2006, Lu et al 2013

- 10^3 pulsars with P < 100 y

Pfahl & Loeb 2004

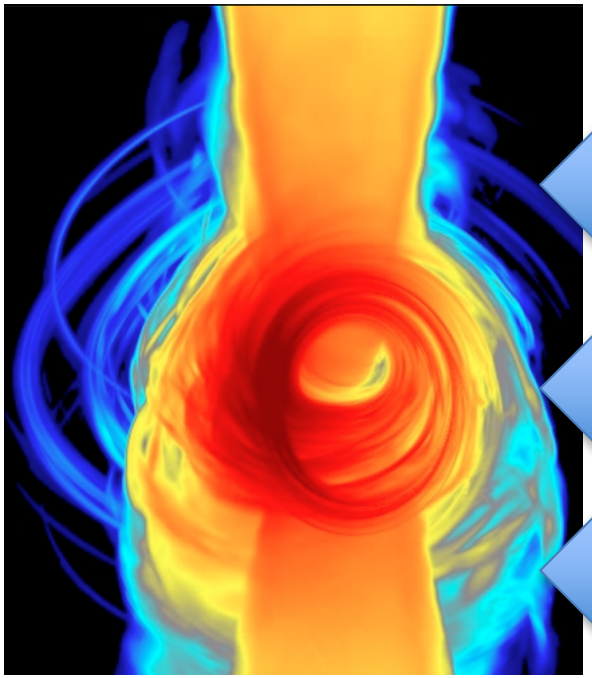


Revised PSR Sensitivity

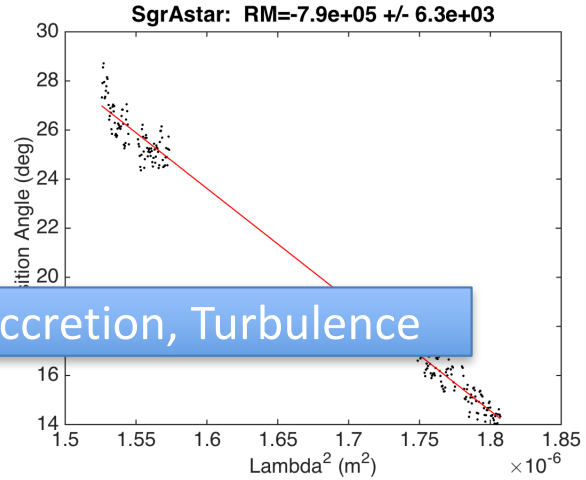


Macquart & Kanekar 2014

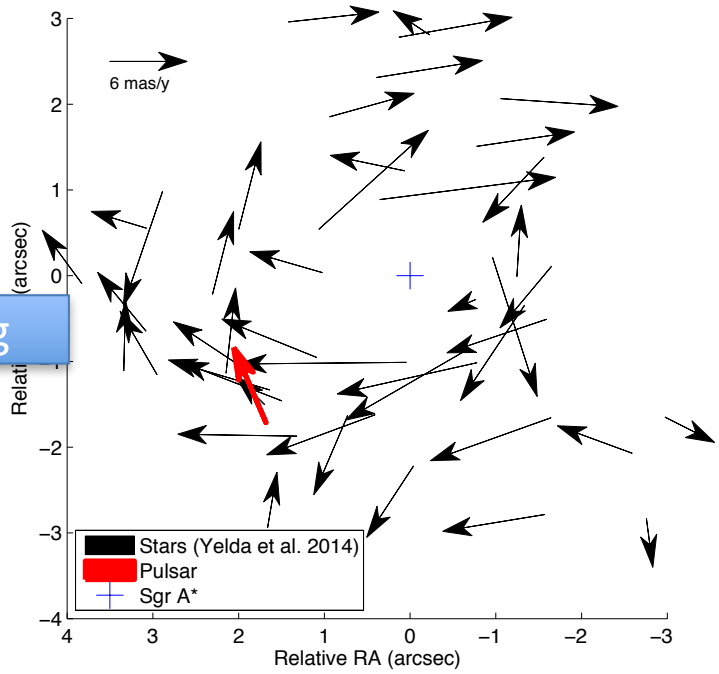
Exciting Times in the Galactic Center



Accretion, Turbulence



Environment, Scattering, Timing



Jets, Disks, Temperature